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TITLE: DEVELOPMENT OF A MULTI-FREQUENCY JET VENTILATOR FOR USE UNDER BATTLEFIELD CONDITIONS

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APPENDIX B
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SMALL BUSINESS INNOVATION RESEARCH PROGRAM
PHASE 1 — FY 1986
PROJECT SUMMARY

Topic No. A86-214 Military Department/Agency Army

Name and Address of Proposing Small Business Firm

Scientific Research Associates, Inc.
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Name and Title of Principal Investigator

Bernard C. Weinberg, Senior Research Scientist

Title Proposed by Small Business Firm

Development of a Multi-frequency Jet Ventilator for use under Battlefield Conditions

Technical Abstract (Limit your abstract to 200 words with no classified or proprietary information/data.)

The primary objective of the Phase I study was to investigate the effectiveness of ultra-high frequency jet ventilation in sustaining wounded with penetrating chest injuries. To this effect, an experimental program was undertaken to simulate such injuries on animals by creating a reproducible wound in the laboratory. A broncho-pleural cutaneous fistula was surgically induced in ten pigs and their progress with three different modes of ventilation: conventional, conventional jet and ultra-high frequency jet, were monitored. Blood gases and vital signs were taken and the flow through the fistula was measured. The data obtained in these experiments demonstrate a significant benefit in oxygen loading as evidenced by an improved a/A ratio during ultra-high frequency jet ventilation as compared to either conventional jet or conventional ventilation. There was also a marked decrease in the gas flow through the bronchopleural fistula in ultra-high frequency jet ventilation as compared to the other two modes. Statistical analyses confirm that the observed differences were statistically significant. These results indicate that ultra-high frequency jet ventilation offers significant advantages and benefits in ventilating lungs in which a large bronchopleural fistula has formed. A secondary objective was to investigate methods for measuring the resonant frequency of the lung system in conjunction with jet ventilation. Results demonstrated the feasibility of the proposed approach.

Anticipated Benefits/Potential Commercial Applications of the Research or Development

The results of the Phase I experimental program indicate that the ultra-high frequency jet ventilator could be very beneficial in ventilating wounded with penetrating chest injuries. In view of its portability and rugged construction, it would find application on the battlefield. Under such conditions it would be useful in the emergency treatment of wounded. It would also find application in both a military and civilian hospital setting in those cases where other methods of ventilation are ineffective or could be detrimental to the patient. The long term goal for the civilian sector is to have the portable ventilator built and distributed to trauma units.

List a maximum of 8 Key Words that describe the Project.

Ultra-high frequency jet ventilator, penetrating chest wounds

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I. INTRODUCTION

A significant factor in the survivability and eventual recovery of battlefield wounded is that medical attention be given promptly, in many instances prior to reaching a MEDEVAC Unit. One of the more serious cases is that of wounds directly involving the chest necessitating ventilatory support to sustain life. Conventional methods may be of marginal value, and could even further hinder recovery by adding to chest trauma. Clearly, a portable ventilation device that could be used on site by medics without stressing the chest area would be very valuable.

In recent years there has been increased interest in novel ways of ventilating patients (cf. Refs. 1, 3, 4), to better treat their diseases while not exaggerating or introducing other disorders that may result as a consequence of the ventilating procedure. The most common way of ventilating a patient is to mimic the normal breathing pattern of healthy individuals. In this process, air is convected through the lungs at the breathing frequency by pushing fresh gases through the airways either by applying a positive pressure at the airway inlet or a negative pressure around the thorax. In either case, the frequency is kept at the breathing frequency while the tidal volume is equal to the amount inhaled during normal breathing.

The procedure, while very effective in a nontraumatized chest, may not be suitable for patients suffering from penetrating chest wall injuries or severe trauma to or near the thoracic cavity. In these cases, the patient's lungs do not respond properly either due to alveolar damage resulting in reduced quantities of 02 reaching the blood, or due to the creation of fistula tracts. Other clinical examples of situations where normal breathing frequency and tidal volumes might be detrimental to the well-being of the patient are: (1) Bronchoplural Fistula, (2) Adult Respiratory Distress Syndrome, and (3) Flail Chest.

Positive pressure ventilation has been utilized for pulmonary support for the last 25 years. Over the past 5 to 10 years, detrimental aspects of positive pressure ventilation have come to the foreground. These associated problems include baro-trauma, decrease in cardiac output with resultant decreased tissue perfusion, and the necessity for tight occlusion of the upper airway, which can frequently result in tracheal stenosis and other tracheal complications. High frequency jet ventilation has been prevalent in Europe for

the last ten years. Rather than supplying breaths at the normal breathing frequency of 1/3 Hz (20 breaths/minute), in high frequency jet ventilation breaths are delivered at frequencies as high as 2 Hz (120 breaths per minute). Its major advantage over positive pressure ventilators of the usual type is the decreased intrathoracic pressure leading to less cardiac impairment and, therefore, fewer problems associated with decreased tissue perfusion with oxygen. The smaller tidal volume used by high frequency jet ventilators also results in less baro-trauma. Ventilation of this nature can be accomplished even with an uncuffed endotracheal tube, therefore, eliminating the problems associated with pressure necrosis of the trachea.

Recently, attempts have been made to use a different mode of ventilation, i.e. ultra-high frequency jet ventilation. This process is completely different from the two previous processes because it augments mass transport rather than relying upon the movement of gases in bulk quantities into the gas-exchanging areas of the lungs. It offers all the advantages of the high frequency jet such as low intrathoracic pressure and negligible effect on cardiac output, and could be used either with a cuffed or uncuffed endotracheal tube. Its further usefulness is that the process by which it achieves enhanced ventilation, augmented mass transport, will establish the highest possible oxygen content in the arterial blood and will be most efficient in the elimination of carbon dioxide. Because of minimal chest wall movement associated with the technique, it will lend itself to use in patients with penetrating chest wall wounds and/or trauma of the rib cage.

Ultra-high frequency jet ventilation will augment mass transport only at very high frequencies typically in the range of 5 Hz to 20 Hz (300 to 1200 breaths per minute). Although there is extensive theoretical and experimental basis for the process (cf. Ref. 4, 8, 9, 10, and 11) there are only limited positive clinical findings reported in the literature. The reason for this situation is that the methods previously used to produce the ultra-high jet frequencies could not deliver the required tidal volumes to adequately ventilate the patient.

Recently, we at Scientific Research Associates in conjunction with Hartford Lung Physicians have constructed a prototype multifrequency jet ventilator which does not have the limitation mentioned above and has been successfully used in laboratory and clinical tests on pigs. The test results which are described in Appendix 1 have been extremely positive and encourage us

to believe that our ventilator can be of significant benefit to patients suffering from injuries and diseases of the type described above. Since the portable model of the ventilator is rugged and lightweight, and can easily be maintained and sterilized, containing only one moving part - a solenoid actuated pneumatic valve, we believe that it could be very attractive for use under battlefield conditions or other emergency situations. A more complete description of the operation of the ventilator is given in Section 3.

More recently the in-hospital version of the ventilator, the APT 1010, has been used to ventilate patients with ARDS under FDA approved trials at Hartford Hospital. As of 1 June 1987, ten patients have been ventilated on the APT 1010, with some up to 10 days. Four out of five patients with ARDS of less than forty eight hours have recovered from their lung injury when ventilated on the APT 1010. Although no statistical conclusions as yet can be drawn from these results it is noteworthy that the national average for recovery from ARDS is approximately 30%. In addition, since ARDS can be a complicating factor in lung trauma, the encouraging results obtained in the FDA trials indicate that this form of ventilatory support may be useful for treating some of the sequelae of penetrating chest wounds.

As noted above, our multifrequency jet ventilator would be advantageous for use with penetrating chest wounds. Further, it could also be of benefit in the presence of a noxious chemical environment where paralysis of the chest area or burning and scarring of the internal membranes could lead to impaired breathing. In such cases, which usually occur under adverse conditions where highly trained medics are unavailable but immediate care is required, the multifrequency jet ventilator would be of great value. Transcutaneous cricothyroidostomy could be administered by relatively untrained medics employing our ventilator to give the required immediate care until the patient is evacuated to a more suitable environment. Thereafter, our ventilator could be operated in its normal mode. Furthermore, the augmented mass transport that results may also facilitate the removal of the noxious gases more rapidly.

The results of the animal experiments conducted to date (cf. Appendix 1 for a complete description of these studies) indicate that the present device was superior to conventional positive pressure ventilation in providing the highest oxygen levels in the blood. These experiments, however, do not precisely simulate injuries and diseases sustained under battlefield conditions. It was, therefore, the principal objective of the Phase I effort to conduct a series of

animal experiments that would establish the efficacy of the ventilator and the ventilation technique for treating battlefield sustained injuries, namely penetrating chest wounds.

The other objective of the Phase I research effort was to investigate a method for measuring the resonant frequency of the lung system that could be used in conjunction with the multifrequency jet ventilator. Our experiments with pigs have indicated that significant improvement in oxygenation can be obtained at a unique "optimum" frequency, which varies from animal to animal. It is expected that similar behavior exists for humans. We believe that this frequency may be related to the natural or resonant frequency of the lungs. Furthermore, the method used to measure the resonant frequency could also be applied to determining the patient's lung mechanics, thereby aiding in the evaluation of his recuperative progress.

The results of SRA's Phase I study for a simulated penetrating chest wound in an animal show that ultra-high frequency jet ventilation was superior to other forms of ventilation by enhancing O_2 loading. In addition, there was significantly lower flows through the broncho-pleural fistula when the animal was ventilated with the ultra-high frequency jet. Although the data collected were for laboratory controlled reproducible injuries in animals, these results clearly indicate that ultra-high frequency jet ventilation could also be effective in sustaining humans with similar types of injuries.

In the following sections the report describes in detail the experiments conducted, the statistical analysis of the data and the conclusions reached. The report is divided into five sections. Section 2 is a summary of the Phase I technical objectives. Section 3 provides a brief description of the multifrequency jet ventilator used in the experimental program. This is followed in Section 4 with a description of the experimental program, protocol, results and a statistical analysis of the data. In Section 5, a description of the apparatus for measuring the resonant frequency of the lung system is described, as well as a discussion of the results obtained. Section 6 contains the conclusions and recommendations.

2. PHASE I TECHNICAL OBJECTIVES

The Phase I technical objectives were as follows:

1. Determine the effectiveness of three different modes of mechanical ventilation in treating simulated penetrating chest injuries by performing laboratory tests on animals employing the following modes of ventilation:
   (a) conventional ventilation (6 - 30 BPM)
   (b) high frequency jet (120 - 180 BPM)
   (c) ultra-high frequency jet (> 300 BPM)
2. Construct a device that could be used in conjunction with the multifrequency jet ventilator to measure the resonant frequency of the lung system and investigate what relation exists between the natural frequency and the 'optimum' ventilation frequency.

3. DESCRIPTION OF THE MULTIFREQUENCY JET VENTILATOR

As described in Section 1, augmented mass transport can be used beneficially to ventilate the lungs. This phenomenon combines two diverse disciplines, fluid mechanics and pulmonary medicine. The collaboration of Scientific Research Associates and Hartford Lung Physicians, each with expertise in their respective fields, offers a unique opportunity to investigate this area from multiple viewpoints, leading to a better understanding of the physical processes that are involved. Indeed, the design development and construction of our prototype high frequency jet ventilator could not have been accomplished without this interdisciplinary collaboration.

The device we have built is a multifrequency jet ventilator of the solenoid valve type. It can operate throughout the useful frequency range including those employed in positive pressure ventilation, high frequency jet and the present ultra-high frequency jet, with the frequency chosen to best treat the patient. The operating frequency can be varied from 1/15 Hz (4 breaths/min) to more than 50 Hz (3000 breaths per minute) and the inspiratory time can range from 5% to 95%. Specifically, one is able to vary the frequency, the driving pressure of the gas, and the fraction of the cycle time during which the solenoid valve is open. These in turn control tidal volume,

the I/E (inspiratory to expiratory) ratio, and the respiratory rate of the patient. The major components of the ventilator include a control module (electornic control and power system), a power module (solenoid valve and pressure regulator) and a motive module (motive nozzle, entrainment plus humidification system). The electronic controlling device is specifically designed to enhance the opening and closing of the solenoid valve, such that even at high frequencies a virtually square wave pattern of gas is emitted with each pulse. This allows larger tidal volumes for a given driving pressure, frequency and inspiratory time.

The ventilator works on the following basis: A high pressure gas source enters into the solenoid valve, the electronic controlling device opens and closes the solenoid valve according to preset conditions. The time that the valve is open is set by the frequency and the inspiratory time. This plus the driving pressure will result in a given tidal volume. The gas is then transported through low compliant tubing to the motive nozzle in the entrainment module. The entrainment module has a low velocity flow of humidified gas through it; part of which is entrained by the high velocity jet issued by the motive nozzle during the inspiratory part of the cycle, the exhaled gas is removed along with the low velocity gas flow through the entrainment module.

In the past, one of the major obstacles in the way of the development of such an ultra-high frequency jet ventilator was the inability to deliver adequate tidal volumes to the patient in the desired range of frequencies. The joint efforts of Scientific Research Associates and Hartford Lung Physicians were able to overcome this difficulty by introducing several novel innovations into the design. These included a specialized electronic circuit to drive the solenoid valve, allowing it to open and close significantly faster than in its normal mode of operation and aerodynamically designed components for use in the entrainment module to efficiently entrain oxygen rich humidified gas and to remove exhaled CO_2.

There are two versions of the APT 1010 multifrequency jet ventilator, an in-hospital unit and a portable unit. Although both versions have the same basic components there are several distinct differences between them. The in-hospital unit, as required by the FDA, has built-in safety alarm systems as well as other monitoring equipment. It is intended for prolonged use in the intensive care unit and hence mobility is not a significant concern. In order

to effect the desired functions the unit is microprocessor controlled. Such a microprocessor system permits many enhancements which have been included in the APT 1010, viz. a sophisticated data acquisition system and a data archival and retrieval system. It should be noted, however, that subsequent prototype units have been reduced in size to an extent that, with an appropriate battery power source, could be made portable if deemed necessary.

In contrast to the in-hospital unit, the portable unit is intended for emergency, temporary use and therefore does not require the complete complement of sensors and safety alarm systems. This permits the unit to be built with simplified electronic controls. Hence, the unit can be made extremely small, light weight and rugged and requiring minimal power consumption.

4. SIMULATION OF A PENETRATING CHEST WOUND

4a. Materials and Methods

As noted previously, the pig was used as the test animal. There are several reasons for this. First, large animals can be readily obtained, in weights approaching that of an adult human. Second, since the pig's lungs are less efficient than those of a human, being less compliant and having less collateral ventilation between alveoli positive conclusions reached in the study would carry over to humans. For other animals such as dogs results may be inclusive. Third, the pig also has other physiological similarities with humans. The experiments were conducted at the Hartford Hospital Animal Laboratory where our previous tests were held.

Yorkshire female swine weighing between 80 and 100 pounds were used as test animals. No two were from the same litter. The animals were supplied by the breeder

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Prior to surgery, the preanesthesia administered to the animal was atropine with dosage .02 mg/lb and acepromezine with dosage 5 mg/lb. During the experiments, Nembutal (pentobarbital) and Pavulon (pancrium bromide) were administered intravenously at the rate of 21 mg per half hour and 3-6 mg per half hour, respectively. At the conclusion of the experiment the pig was given 40 meq of potassium chloride in a 20 cc bolus as the euthanesia agent.

After the animals were sedated and anesthetized a carotid arterial line was placed and a Swan-Ganz catheter was inserted through the internal jugular artery. Additional venous accesses were also placed. The animal was then intubated and placed on the APT 1010 ultra-high frequency jet ventilator and optimal gas exchange was achieved by varying the driving pressure (10-50 psi) and/or the frequency in the range of 7.5 Hz and the I/E ratio was set to 30%. Following this, the animal was switched to a volume limited conventional ventilator and tidal volume and respiratory rate were varied to achieve optimal gas exchange. Respiratory rates varied from 8-20 breaths per minute and tidal volumes between 600-1200 ml. During this period baseline arterial blood gases and cardiac output were obtained and arterial pressure was monitored as well as other physiological data, i.e. pulse, blood pressure, pulmonary artery pressure (PAP), pulmonary capillary wedge pressure (PCW) and pH. The mean arterial pressure and saturation were computed using the collected data.

After the stabilization period and having obtained the baseline values surgery began. The animal was placed back on the APT 1010 and a thoracotomy was performed. A right upper lobe lobectomy was then carried out. The bronchial stump was connected to a Fleishe pneumotac through a plastic cannula and rubber tubing of similar diameter. The Fleishe pneumotac has previously been calibrated for various flows in the pulmonary laboratory. The thoracic cavity was left open to the atmosphere. This surgical procedure was easily reproducible, which was important in obtaining statistically meaningful data. During the procedure the pig was ventilated using the ultra-high frequency jet ventilator at 7.5 Hz. This mode of ventilatory support was requested by the surgeon, Dr. Rocco Orlando, since it minimized chest movement and permitted the procedure to be easily performed.

The experimental procedure called for randomization of the three different modes of ventilation, i.e. ultra-high frequency jet ventilation (frequency of 5-10 Hz.), conventional ventilation (frequency 1-3 Hz.) and conventional ventilation with 8-20 breaths per minute. Each experimental sequence consisted of randomly selecting one of the three modes of ventilation, followed by random selection of the second and then the third. The animal was allowed to equilibrate for 10 minutes before any hemodynamic or arterial blood gas measurements were made in each mode of ventilation. At the end of completing one series of experiments the randomization again was carried out. If the animal survived, three sets of data were collected for each animal in each of

the ventilatory modes, or nine data points were gathered for each experimental animal. Hemodynamic data consisted of arterial blood pressure, cardiac output, pulmonary artery pressure and pulmonary capillary wedge pressure. Arterial blood gases were analyzed using a Corning arterial blood gas analyzer. Bronchopleural fistula flow was obtained by integrating the flow curves obtained through the Fleishe pneumotac using a K+E planometer. The Fleishe pneumotac was checked at the end of the experiment to ensure that no changes in calibration factors had occurred. A complete listing of all data taken and definitions of parameters are given in Table 1.

Eleven experiments (with eleven animals) were conducted. Of these eleven, data taken in ten experiments were used in the statistical analysis due to the early demise of animal #5. The data used in the statistical analysis are shown in Tables 2 through 4. Table 2 shows the raw data in spreadsheet form, while Tables 3 and 4 present the data for the unbalanced and balanced design, respectively (cf., Section 4b). The data was analyzed using STATGRAPHICS, a PC based statistical package marketed by STSC, and all variables were considered. A value of α=.05 was considered significant.

4b. Statistical Analysis

The hypothesis that was tested in the series of experiments is that ultra-high frequency jet ventilation is superior to other modes of ventilation in the physiological simulation of penetrating chest wounds in pigs, i.e. a bronchoplueral fistula. The hypothesis was tested by considering a sequence of ten experiments employing the protocol described previously and measuring the physiological animal parameters and flow through the fistula to determine how well the animal was ventilated. Statistical analysis of these data is used to draw conclusions concerning the veracity of the hypothesis.

The goal of the experimental design is to examine the performance of three modes of ventilation by eliminating the test order effect and screening out the test timing and animal effects. Special care was taken in designing the experimental setup that was employed. In view of the nature of the present series of animal experiments associated with the variability of the animals themselves as well as their progressive deterioration as the test proceeded, test timing, which may be a significant effect, must be taken into account. Hence, the following conditions were met for the duration of the experiments:

(1) Every testing day the procedure for running any particular ventilator was kept the same;

(2) The system parameter setup for running one particular ventilator was kept the same;

(3) A three-way layout randomized block design was employed.

With regard to item (3) the randomized block design is described in the previous section. An a posteriori estimate of randomness was conducted at the termination of the experimental program. The results of this test which confirm the randomness of the data are shown in Table 5. It should be noted that the randomized block design differs somewhat from the standard 3x3 Latin square design in that each sequence of the three ventilator tests per animal is randomly chosen before the beginning of the sequence rather than at the outset of the experiment.

The experiment has the following tabulated design:

		Ventilator		
Animal #	Test timing order	A	B	C
1	t1	(1)	(m)	(n)
	t2	( )	( )	( )
	t3	( )	( )	( )
2	t1	( )	( )	( )
	t2	( )	( )	( )
	t3	( )	( )	( )
3	t1	( )	( )	( )
	t2	( )	( )	( )
	t3	( )	( )	( )
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
10	t1	( )	( )	( )
	t2	( )	( )	( )
	t3	( )	( )	( )

where l, m and n is a random choice of permutations of the three ventilators which can eliminate the test order effect.

The strategy of the three-way layout randomized block design can be summarized as follows; there are an equal number of observations in the cells. It includes single effects and two and three factcr interactions. An analysis of variance was conducted and the main effects and interactions were considered. Mathematically, the formulation can be expressed as follows:

$$Y_{ijkm} = \mu + \alpha_i^A + \alpha_j^B + \alpha_k^C + \alpha_{ij}^{AB} + \alpha_{jk}^{BC} + \alpha_{ik}^{AC} + \alpha_{ijk}^{ABC} + e_{ijkm} \qquad (1)$$

where

$$e_{ijkm} \sim \text{IIDN}\ (0,\ \sigma^2)$$

and

μ =	the general mean,	$\hat{\mu} = y...,$
σ_i^A =	the ventilator effect,	$\hat{\alpha}_i^A = y_i... - y...,$
α_j^B =	the animal effect,	$\hat{\alpha}_j^B = y._j.. - y...,$
α_k^C =	the test timing effect,	$\hat{\alpha}_k^C = y.._k. - y...,$
α_{ij}^{AB} =	two-factor A,B interaction,	$\hat{\alpha}_{ij}^{AB} = y._j.. - y_i... - y._j.. + y...,$
α_{jk}^{BC} =	two-factor B,C interaction,	$\hat{\alpha}_{jk}^{BC} = y._{jk}. - y._j.. - y.._k. + y...,$
α_{ik}^{AC} =	two-factor A,C interaction,	$\hat{\alpha}_{ik}^{AC} = y._i._k. - y_i... - y.._k. + y...,$
α_{ijk}^{ABC} =	three-factor A,B,C interaction	$\hat{\alpha}_{ijk}^{ABC} = y_{ijk}. - y._j.. - y._{jk}. - y_i._k. + y_i...$ $+ y._j.. + y.._k. - y...,$

with the following analysis of variance table:

Source	SS	Degreees of Freedom	E(MS)
A main effects	$SS_A = JKM \sum_i (\hat{\alpha}^A_i)^2$	I - 1	$\sigma^2 + JKM\sigma^2_A$
B main effects	$SS_B = IKM \sum_j (\hat{\alpha}^B_j)^2$	J - 1	$\sigma^2 + IKM\sigma^2_B$
C main effects	$SS_C = IJM \sum_k (\hat{\alpha}^C_k)^2$	K - 1	$\sigma^2 + IJM\sigma^2_C$
AB interactions	$SS_{AB} = KM \sum\sum_{ij} (\hat{\alpha}^{AB}_{ij})^2$	(I - 1)(J - 1)	$\sigma^2 + KM\sigma^2_{AB}$
BC interactions	$SS_{BC} = IM \sum\sum_{jk} (\hat{\alpha}^{BC}_{jk})$	(J - 1)(K - 1)	$\sigma^2 + IM\sigma^2_{BC}$
AC interactions	$SS_{AC} = JM \sum\sum_{ik} (\hat{\alpha}^{AC}_{ik})^2$	(I - 1)(K - 1)	$\sigma^2 + JM\sigma^2_{AC}$
ABC interactions	$SS_{ABC} = M \sum\sum\sum_{ijk} (\hat{\alpha}^{ABC}_{ijk})^2$	(I - 1)(J - 1)(K - 1)	$\sigma^2 + M\sigma^2_{ABC}$
Error	$SS_e = \sum\sum\sum\sum_{ijkm} (y_{ijkm} - y_{ijk\cdot})^2$	IJK(M - 1)	σ^2
Total about grand mean	$\sum\sum\sum\sum_{ijkm} (y_{ijkm} - y\ldots\cdot)^2$	IJKM - 1	

where

$$\sigma^2_A = (I - 1)^{-1} \sum_i (\alpha^A_i)^2$$

$$\sigma^2_B = (J - 1)^{-1} \sum_j (\alpha^B_j)^2$$

$$\sigma^2_C = (K - 1)^{-1} \sum_k (\alpha^C_k)^2$$

$$\sigma^2_{AB} = (I - 1)^{-1} (J - 1)^{-1} \sum\sum_{ij} (\alpha^{AB}_{ij})^2$$

$$\sigma^2_{BC} = (J - 1)^{-1} (K - 1)^{-1} \sum\sum_{jk} (\alpha^{BC}_{jk})^2$$

$$\sigma^2_{AC} = (I - 1)^{-1} (K - 1)^{-1} \sum\sum_{ik} (\alpha^{AC}_{ik})^2$$

$$\sigma^2_{ABC} = (I - 1)^{-1} (J - 1)^{-1} (K - 1)^{-1} \sum\sum\sum_{ijk} (\alpha^{ABC}_{ijk})^2$$

In each cell of the experimental design, one observation is taken, i.e., m=1 in Equation (1).

After the means and variances are of the experimental data are calculated the following examinations are carried out:

i. Addressing the differences in the ventilator effect
ii. Testing the significance of main effects
iii. Testing the significance of two factor interactions
iv. Testing the significance of three factor interactions
v. Testing the adequacy of the model employed

Two hypothesis testing procedures are considered:

1) F-Test - testing whether one particular effect is signifiant, e.g.,

$$Ho = \alpha_i^A = 0 \ \forall_i$$

we reject Ho at the 100α% significance level if

$$\frac{IJK(M-1)SSA}{(I-1)SSe} > F_{(I-1),\ IJK(M-1);\ \alpha} \qquad (3)$$

and accept Ho is the inequality runs the other way.

MS	F-Ratio Test	Ho
$SS_A/(I-1)$	$IJK(M-1)SS_A/(I-1)SSe$	$\alpha_i^A = 0 \quad \forall i$
$SS_B/(J-1)$	$IJK(M-1)SS_B/(J-1)SSe$	$\alpha_j^B = 0 \quad \forall j$
$SS_C/(K-1)$	$IJK(M-1)SS_C/(K-1)SSe$	$\alpha_k^C = 0 \quad \forall k$
$SS_{AB}/(I-1)(J-1)$	$IJK(M-1)SS_{AB}/(I-1)(J-1)SSe$	$\alpha_{ij}^{AB} = 0 \quad \forall ij$
$SS_{BC}/(J-1)(K-1)$	$IJK(M-1)SS_{BC}/(J-1)(K-1)SSe$	$\alpha_{jk}^{BC} = 0 \quad \forall jk$
$SS_{AC}/(I-1)(K-1)$	$IJK(M-1)SS_{AC}/(I-1)(K-1)SSe$	$\alpha_{ik}^{AC} = 0 \quad \forall ik$
$SS_{ABC}/(I-1)(J-1)(K-1)$	$IJK(M-1)SS_{ABC}/(I-1)(J-1)SSe$	$\alpha_{ijk}^{ABC} = 0 \quad \forall ijk$
$SSe/IJK(M-1)$		

2) T-Test - testing whether the dfference between two treatments is significant, e.g.,

$$Ho = \alpha_1^A = \alpha_2^A$$

We have a confidence interval with 100α% significance level as

$$(\hat{\alpha}_1^A - \hat{\alpha}_2^A) \pm t_{\nu,\alpha/2}\, S \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \qquad (5)$$

We accept Ho if the calculated value is within this interval and reject Ho otherwise. (Note that $\sigma^2(1/n_1 + 1/n_2)$ is the variance of $\alpha_1^A - \alpha_2^A$, and S^2 is the unbiased estimate of σ^2, ν is the degrees of freedom associated with S^2, n_1, n_2 are the observation numbers of α_1 and α_2, respectively.)

The STATGRAPHICS statistical package was used to obtain the statistical analysis presented herein. It should be noted that two factor and three factor analysis can only be obtained with a balanced design, i.e. the same number of cells in each experiment. During the experimental program of the eleven animal experiments conducted, ten were used in the analysis as per the original protocol, since one animal (number 5) died early in the experiment. Of these ten, eight had nine entries per experiment, three ventilators by three sequences. However, in experiment #2 four sequences were conducted and in experiment #3 only two sequences were completed. Hence for the balanced analysis nine experiments were employed (using the first three sequences of experiment #2, while for the unbalanced design the full ten experiments were considered.

In Tables 6 through 8 the analysis of variance and significance tests are presented for the a/A ratio and flow through the broncopleural fistula. Table 9 summarizes these results. The graphical data are presented in Figures ___. For the sake of brevity, selected balanced design results are shown. It should be noted that there was no discernible difference between the balanced and unbalanced design results.

From the statistical analysis of the a/A ratio it can be concluded that

(i) Three main effects: animal, ventilator and sequence, are significant effects in determining the a/A ratio of the treatment. Other terms in Eq. (1) appear not to be significant.

(ii) The residual analysis indicates that 90% of the a/A ratio variation of the treatment can be interpreted by the chosen mdoel. The residual effect does not reject the adequacy of the employed model.

(iii) For different ventilators, the resulting a/A ratio is significantly different, as shown in Fig. 2. The test of significance is performed and the results are displayed in Table 7c. It indicates that UHFJV provides the highest a/A ratio among the three different modes of ventilation. This conclusion is based upon the unanimous agreement under 95% confidence interval, 99% confidence interval, Tukey test and Scheffe test.

4c. Discussion of Results

The data obtained in this experiment demonstrated a significant benefit in oxygen loading, as evidenced by an improved a/A ratio during ultra-high frequency jet ventilation, as compared to either conventional jet ventilation or conventional ventilation. In Figs. 2, 3 and 4 the mean a/A ratios at the 95% confidence level are plotted as functions of ventilator, sequence and animal (experiment #), respectively. With regard to ventilator dependence (cf. Fig. 2), it is readily evident that ultra-high frequency jet ventilation is superior to other modes of ventilation. This is borne out in the significance levels that are given in Table 7c and are summarized in Table 9. It is noteworthy that even at 99% confidence level, the a/A ratio obtained for the ultra-high frequency jet ventilator still demonstrates superiority over the other forms of ventilation (cf. Fig. 5).

There was a marked decrease in the gas flow through the bronchopleural fistula in ultra-high frequency jet ventilation as compared to the other two modes of ventilation. Figure 6 demonstrates this result convincingly, where the flow through the bronchopleural fistula is plotted as a function of mode of ventilation for the 95% confidence level. This result is further confirmed in Tables 8c and 9 in which the significance levels for differences in ventilators are presented. In addition, the flows through the bronchopleural fistula as a function of ventilator, sequence and animal are presented in Figs. 6, 7 and 8.

Hemodynamics did not show any significant difference in any of the modes of ventilation. Although the PCO_2 was somewhat lower in the conventional jet ventilation than in either of the other modes, this did not reach any clinical significance, although it did result in a statistically significant

difference. These results are shown in Figs. 9 and 10 in which O_2 delivery and O_2 content as functions of ventilation mode for 95% confidence level are presented.

In studying the acoustic and fluid dynamics of the lung system it is helpful to employ electrical analogies. Thus, flow and pressure become current and voltage, respectively, and viscous resistance, compliance and mass can be related to electrical resistance, capacitance and inductance, respectively. Using this analogy we can gain insight into the mechanisms controlling the ventilation in the animals and assist in the explanation of the observed results.

One can view the airways as a resistance, first in series, then in parallel, ending in a finite capacitance (cf. Fig. 1). One would then anticipate that under conditions of conventional ventilation the infinite capacitance afforded by a bronchopleural fistula (BPF) would result in uneven distribution of gas, favoring ventilation down the pathway of infinite capacitance. Typical jet ventilation frequency, i.e., 1-3 Hz., employs smaller tidal volumes. This effectively reduces the percent of the total capacitance used for gas exchange in the lungs, allowing more favorable competition with the infinite capacitance of the BPF.

The APT 1010, used in this experiment, uses augmented diffusion as well as convection as its means of ventilation. Gas exchange therefore relies upon creation of concentration gradients to some extent, as well as convective and Taylor dispersion-type mechanisms. The low tidal volumes, relative stable lung volumes and high frequencies would therefore negate the effect of the infinite capacitance afforded through the bronchopleural fistula. This would then result in a redistribution of gas throughout the lung unit in a more unified manner, decreasing the overall ventilation of the bronchopleural fistula and improving ventilation in a previously hypoventilated area. The results of this study suggest that this is the case. There has been a clear difference in the a/A ratios, suggesting better matching of ventilation and perfusion throughout the lung zones as compared to conventional ventilation and conventional jet ventilation. There has also been a marked diminution in the flow through the bronchopleural fistula during ultra-high frequency jet ventilation, as compared to the other two modes.

The experimental design allowed us to single out the ventilators as the causative agent for these discrepancies. The randomization of mode of ventilation in each animal negated the possibility that time would be a factor or that changing from conventional to ultra-high frequency jet ventilation or any of the other possible permutations might result in improvement in gas exchange, irrespective of the physiological changes that occured in the lung. Furthermore, when one looks at O_2 loading, i.e., a/A ratio, as a function of flow through the bronchopleural fistula, one does not see a discernible relationship. This suggests that the a/A ratio, which in this model is mainly dependent on ventilation perfusion matching, is independent of flow through the bronchopleural fistula. This would necessarily be the case if gas exchange was diffusion-dominated rather than dependent upon bulk gas flow. Relative to the total pulmonary capacitance there is no significant difference between the volumes delivered in these two ventilatory modes, yet the a/A ratio and BPF flow were significantly better in the UHFJV group. In this regard, the gradient for gas exchange is actually slightly greater in the intact bronchial alveolar units (PAO_2 - PVO_2) than in the bronchopleural fistula units (PAO_2 - $P_{AMB}O_2$). The reduction in bronchopleural fistula flow at the high frequencies is probably not relying soley on gases moving down a concentration gradient. In fact, resistance times capacitance (RC) constants are more likely responsible for the more even distribution of gas exchange achieved with UHFJV. The tidal volumes employed in UHFJV are about 60% of those achieved in HFJV. This, of course, would not be the case using large tidal volumes at conventional respiratory frequencies.

In analyzing the data we have taken into account the time from the start of the experimentation after surgery was completed, as well as the relationship of the preceding type of ventilation on gas exchange, we have found that there was no significant relationship between switching from one type of ventilation to another with respect to gas exchange, since the time factor was equalized for all three modes by the randomization of the experiment.

5. RESONANT FREQUENCY OF THE LUNG SYSTEM

5a. Background

The current methodology employed to determine the physiological changes to the lung while a patient is being sustained on a jet ventilator relies either upon an examination of chest X-rays and/or the determination of the compliance of the lung. The former gives a qualitative measure while the latter requires that the patient be removed temporarily from the jet ventilator. Relying solely on arterial blood gas analysis may not be sufficient to detect therapeutic changes to the lung but may only indicate how well the patient is being ventilated. Hence, a method that could give a quantitative measure of changes to the lung while being ventilated, namely changes in lung mechanics, would be a valuable tool.

For the ultra-high frequency mode of ventilation, determination of lung mechanics including the resonant frequency of the lung system would offer additional benefits. Since the frequency of the pulsed gas stream supplied to the patient is a controlling factor for this mode of ventilation, choosing the appropriate or an 'optimum' frequency would be advantageous. Experience with patients suffering from ARDS in the FDA approved trials at Hartford Hospital being ventilated on the in-hospital version of the APT 1010 has indicated that as a group they can be successfully ventilated at 5 Hz. However, one patient did show marked improvement at a single frequency, which in her case was 5.9 Hz. Although no conclusions can be drawn from this isolated case it is reasonable to expect that there is an optimum frequency which is different for each patient and may be a function of the disease. Further, since the ventilation frequency employed on human subjects is near the resonant frequency of the lung system, the 'optimum' frequency may be related to the resonant frequency.

A robust method for determining lung mechanics is based on forced excitation techniques which was popularized by DuBois (Ref. 2). In this procedure, random or sinusoidal pressure oscillations are induced at the mouth of the subject. By measuring the amplitude and phase angles between the pressure waves and the induced flow the impedance of the lung system can be determined. Each of the two methods, employing either a single sinusoidal frequency or a distribution of random frequencies, offer their own specific advantages. However both techniques require that care be taken in setting up

the apparatus and in interpreting the data. Reference 6 gives a more recent review of the two procedures.

These methods can be readily understood by considering the electrical analogy of the lung system (cf. Fig. 1). In an electrical system consisting of resistors, capacitors and inductors for a given voltage input there is a corresponding current output. The impedance which is the ratio of the two is composed of resistive and reactive components. The impedance will vary as a function of the impressed frequency of the input voltage signal. At resonance, when the voltage and current are in phase, the reactive component vanishes and the impedance is totaly resistive. This electrical analog carries directly over to the acoustic properties of the lung system.

The single frequency technique generates a clean signal which does not require sophisticated spectral techniques to analyze. Impedance and phase angle can be determined, but only at that given frequency. Since in order to obtain a reasonable description of the mechanics of the lung the impedance over the frequency range < 50 Hz is required, this procedure is time consuming, necessitating many individual applications. This method, however, could be used to obtain the resonant frequency by displaying the flow signal versus the pressure signal on an oscilliscope thereby generating a Lisajous figure. At resonance, when the two signals are in phase the figure reverts to a straight line.

An alternate procedure is to use random white noise which has the entire required spectrum (distributed with equal energy) so that the impedance of the lung system as a function of frequency can be obtained in a single procedure. This method, which was successfully employed by Michaelson et al. (cf. Ref. 5), requires that the data be spectrally analysed employing Fast Fourier Transform techniques (FFT). Further, the signal does contain the ensemble of frequencies which may induce noise and must therefore be carefully controlled. Since all information is retained in this process, an inspection of the phase angle between the flow and pressure signals as well as the amplitudes of the pressure and flow signals can be used to determine the resonant frequency.

In view of the ease with which the impedance can be determined in a single run it was chosen as the preferred method and its applicability for use with the ultra-high frequency jet ventilator was investigated. The goal during the Phase I effort was to determine the feasibility of the procedure.

5b. Discussion of Experimental Procedure and Results

The general configuration of the apparatus used for measuring the resonant frequency of the lung system is shown in Fig. 11. It is similar to that used by other researchers, e.g. Michaelson et al. (Ref. 5). A four inch, long throw woofer which is driven by a white noise generator creates the acoustic pressure waves. The driving frequence is low pass filtered at 50 Hz. These waves are transmitted to the mouth of the subject through one inch plastic tubing. Interposed in the line is a pressure transducer and a Fleishe pneumetac, the latter being used to measure the flow. Both flow and pressure histories were recorded and analyzed on a Rockland Dual Channel FFT Signal Analyzer, model 5830B.

In order to verify the performance of the instrumentation, several exploratory tests were conducted. The first involved the measurement of the resonant frequency of a Helmholz resonator (bell jar). The resonant frequency was measured in two ways; using the current experimental set up and with a microphone placed at the mouth of the bell jar. At resonance there is a noticeable increase in sound level as recorded by the microphone. This frequency compared very well with the value obtained from the spectral analysis, i.e. amplitude and phase information. The second set of verification tests involved the measurement of the resonant frequency of the human lung as shown in Fig. 11. The results for the different subjects were in the range of 5 to 7 Hz, well within the limits of published data (cf. Ref. 5).

After completing these preliminary tests the device was deemed reliable for use in measuring the resonant frequency of healty pigs. Due to limited resources we were only able to examine one pig. The animal was anesthesized in the usual manner and placed on the multifrequency jet ventilator. The apparatus was connected to the endotracheal tube and measurements were taken while the animal was being ventilated as well as when it was taken off the ventilator. When the animal was being ventilated the apparatus was connected to the exhilation port of the entrainment module. There was good agreement between the values obtained by the two different methods.

Since the pressure and flow signals were of low amplitude, it is somewhat difficult to discern the resonant value from the random noise signals. Hence, a modification to the usual method was employed. Rather than analyzing the raw signals, we chose to subtract out the random noise and focus upon dfferences in the amplitude of the signals. Thus, if one would look at amplitude difference

as a function of frequency one would observe a zero or near zero value everywhere except at the resonant frequency. In order to effect this procedure an ensemble average of values was used, namely sixteen samples.

Open loop random (white) noise was sampled and averaged sixteen times as was sixteen samples of recorded data taken with the apparatus connected to the animal but disconnected from the ventilator. Recorded data was used since the response time of the Fast Fourier Transform (FFT) analyzer was too long to allow for sixteen samples of actual data to be analyzed in real time. The difference between the open loop (base line) data was compared to the flow and pressure data resulting in the graph showing a resonant frequency of 3.7 Hz (cf. Fig. 12). The peak at 1.9 Hz is probably a system effect (see below). The resonant frequency at 3.7 Hz is further verified by viewing the phase angle between the flow and pressure (cf. Fig. 13) which for this case is precisely 0 degrees.

An additional experiment was performed by binding the chest of the pig. This causes the thorax to be stiffer and hence the resonant frequency should increase. The results of this experiment are shown in figure 14. In this case the resonant frequency has risen to 5.7 Hz, confirming our conjecture. Note that the peak observed in Fig. 12 remained at 1.9 Hz and did not shift further indicating that it is a system effect rather than an actual acoustical lung system resonance.

The procedure and apparatus employed has been shown to be a viable technique for measuring the resonant frequency of the lung system. As noted previously, the purpose of these experiments was to demonstrate feasibility. This objective has been met. Regretfully, in view of the limited resources, extensive tests could not be performed. However, the actual apparatus, although suitable for use in an experimental setting, may not be totally satisfactory for use at the bedside for sick or injured patients. Hence, alternate methods have been briefly investigated that are based upon forced excitation methods. There are two techniques which show promise. The first is the use of the endotracheal pressure signal which is obtained on the in-hospital version of the APT 1010 jet ventilator. By inspecting the waveform, preliminary tests indicate that compliance and resistance can be determined without disconnecting the patient from the ventilator. Another complementary procedure would use the microprocessor in the ventilator, which generates the valve driver signals, to generate the white noise and drive the

solenoid valve. This would eliminate the speaker and could make the apparatus an integral part of the ventilator. These two methods show promise, and could be pursued if deemed desirable in a follow-on effort.

6. CONCLUSIONS AND RECOMMENDATIONS

In view of the body of experimental results and the statistical analyses conducted, we can conclude that ultra-high frequency jet ventilation has significant advantages when ventilating lungs in which a large bronchopleural fistula has formed. The advantages consist of improved ventilation perfusion matching, as evidenced by improved A-a gradients and a/A ratios, as well as decreased flow through the bronchopleural fistula. Ultra-high frequency jet ventilation was also accomplished without any untoward effects with respect to hemodynamic variables or oxygen delivery to the periphery.

The results, which are extremely promising, lead us to believe that our ultra-high frequency jet ventilator could be beneficial in the ventilation of battlefield wounded with penetrating chest injuries of the type investigated. In order to reach this goal, additional research efforts are required. These would include further studies on pigs and would culminate in FDA approved human trials. Efforts would also be directed in the engineering design area in order to assure that the ventilator would be capable of performing in potentially inhospitable environments. These endeavors could be the focus of a follow-on study under Phase II.

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MEASURED AND COMPUTED DATA

- BLOOD GASES
  - PO_2
  - pH
  - PCO_2
  - O_2 SATURATION
- VITAL SIGNS
  - BLOOD PRESSURE
  - PULSE
  - MEAN ARTERIAL PRESSURE
  - PULMONARY ARTERY PRESSURE
  - CARDIAC OUTPUT
  - PULMONARY CAPILLARY WEDGE PRESSURE
- FLOW THROUGH BRONCHOPLEURAL CUTANEOUS FISTULA

GAS EXCHANGE PARAMETERS

- A - a GRADIENT $(760 - 47) * FIO_2 - PCO_2 / 0.8 - PO_2$ (VARIES WITH FIO_2)
- a / A RATIO $PO_2 / [(760 - 47) * FIO_2 - PCO_2 / 0.8]$ (DOES NOT VARY WITH FIO_2)
- O_2 CONTENT - $16.68 * (O_2$ SATURATION) + $(0.0031 * PO_2)$
- O_2 DELIVERY - CARDIAC OUTPUT * O_2 CONTENT * 10

Table 1.

	Time CV	Time UHFJV	Time CJV	pO2 1 CV	pO2 1 UHFJV	pO2 1 CJV	pCO2 CV	pCO2 UHFJV	pCO2 CJV	CO-MEAN CV	CO-MEAN UHFJV	CO-MEAN CJV	PCW CV	PCW UHFJV	PCW CJV
#11 Sequence 1	10:21	10:06	09:54	321.2	365.2	342.5	31.4	21.3	25.1	10.70	9.71	13.07	14		12
#11 Sequence 2	10:32	10:44	10:53	293.8	365.0	391.0	34.8	19.3	16.8	10.41	9.10	9.90	10	10	13
#11 Sequence 3	11:09	11:21	11:31	254.9	354.9	315.6	26.8	21.6	17.0	10.04	9.76	10.80	12	14	14
#10 Sequence 1	10:30	09:50	10:15	165.4	609.9	381.5	34.5	32.7	28.3	7.37	8.09	7.83	11	12	11
#10 Sequence 2	10:56	10:45	11:07	166.6	387.9	374.5	38.6	35.4	27.3	6.94	7.98	8.76	12	15	14
#10 Sequence 3	11:18	11:33	11:43	271.8	274.5	347.7	35.5	30.1	25.4	8.41	8.05	8.91	15	13	12
# 9 Sequence 1	11:06	11:20	10:50	91.7	295.1	445.8	45.7	37.8	37.7	8.65	8.78	8.98	15	12	15
# 9 Sequence 2	11:48	12:01	11:33	55.9	209.3	246.5	39.9	31.8	33.8	8.48	8.75	8.71	12	14	15
# 9 Sequence 3	12:27	12:37	12:16	45.7	159.4	217.0	42.0	26.0	31.4	8.39	8.36	8.65	16	18	18
# 8 Sequence 1	11:55	11:06	11:22	462.1	602.9	563.9	39.1	37.7	38.6	9.76	8.76	9.31	16	18	22
# 8 Sequence 2	12:08	12:34	12:23	419.0	367.0	468.7	36.2	40.0	39.8	9.49	9.28	9.85	18	14	17
# 8 Sequence 3	13:15	12:47	13:00	280.0	407.0	419.0	31.0	38.0	33.0	9.76	9.68	12.11	10	12	12
# 7 Sequence 1	11:45	11:25	12:28	59.5	520.0	246.5	38.1	33.6	28.0	11.59	10.04	10.02	17	19	20
# 7 Sequence 2	13:06	12:52	12:41	48.0	213.3	236.0	31.2	20.6	21.6	11.04	10.76	9.59	16	20	22
# 7 Sequence 3	13:16	13:28	13:43	44.0	129.3	72.5	33.8	19.3	21.0	9.81	12.17	11.14	18	19	15
# 6 Sequence 1	10:45	10:00	10:28	259.2	307.8	296.4	34.2	55.3	22.7	8.48	10.18	10.11	12	13	12
# 6 Sequence 2	11:14	11:26	11:00	265.6	270.0	279.6	30.7	37.1	27.5	9.83	10.51	9.96	11	13	11
# 6 Sequence 3	12:05	11:52	11:40	137.4	201.1	219.4	41.1	40.1	39.5	10.01	10.15	10.06	12	14	10
# 4 Sequence 1	10:25	11:05	10:45	160.7	127.0	140.6	39.9	28.0	31.4	11.24	9.99	11.47	16	19	29
# 4 Sequence 2	11:22	11:55	11:37	57.6	112.2	51.7	33.1	27.9	34.2	9.50	10.79	9.47	19	15	18
# 4 Sequence 3	12:28	12:15	12:42	37.5	111.4	32.0	33.6	23.2	34.9	9.84	9.97	10.61	15	17	16
# 3 Sequence 1	11:47	11:15	11:28	57.2	212.0	58.6	30.7	31.0	29.5	9.26	7.91	9.45	10	10	12
# 3 Sequence 2	12:55	12:00	12:20	31.5	76.2	37.1	23.6	24.8	39.4	4.03	5.57	6.25	10	15	12
# 2 Sequence 1	10:55	11:10	11:27	99.6	97.3	153.6	40.2	31.3	11.5	7.90	8.56	7.04	10	10	9
# 2 Sequence 2	11:47	11:57	12:11	46.6	107.1	80.2	27.3	23.6	27.0	7.83	7.09	7.77	23	12	16
# 2 Sequence 3	12:22	12:33	12:44	51.4	97.1	60.3	27.9	22.5	26.2	7.12	7.09	6.88	15	11	10
# 2 Sequence 4	12:56	13:09	13:19	45.9	68.1	55.7	30.2	21.9	28.4	6.93	5.90	6.16	8	6	8
# 1 Sequence 1	12:05	11:30	13:00	382.0	282.0	81.6	33.6	39.0	23.3	6.08	5.48	7.50	8	10	10
# 1 Sequence 2	12:45	13:34	14:10	91.0	279.0	90.0	40.1	32.2	18.4	6.19	6.19	7.65	10	15	10
# 1 Sequence 3	14:35	13:45	14:28	105.3	302.0	93.5	26.0	29.9	25.8	6.04	5.92	8.18	16	17	12

Table 2a. Complete Physiological Experimental Data.

	Time CV	Time UHFJV	Time CJV	pH CV	pH UHFJV	pH CJV	SAT CV	SAT UHFJV	SAT CJV	FIO2 CV	FIO2 UHFJV	FIO2 CJV	AA RATIO CV	AA RATIO UHFJV	AA RATIO CJV
#11 Sequence 1	10:21	10:06	09:54	7.36	7.47	7.47	0.997	0.998	0.998	1.0	1.0	1.0	0.48	0.53	0.50
#11 Sequence 2	10:32	10:44	10:53	7.33	7.47	7.56	0.996	0.998	0.999	1.0	1.0	1.0	0.44	0.53	0.57
#11 Sequence 3	11:09	11:21	11:31	7.41	7.50	7.58	0.996	0.996	0.998	1.0	1.0	1.0	0.38	0.52	0.46
#10 Sequence 1	10:30	09:50	10:15	7.42	7.38	7.47	0.991	0.999	0.998	1.0	1.0	1.0	0.25	0.91	0.56
#10 Sequence 2	10:56	10:45	11:07	7.40	7.43	7.51	0.991	0.998	0.998	1.0	1.0	1.0	0.25	0.58	0.55
#10 Sequence 3	11:18	11:33	11:43	7.45	7.45	7.55	0.997	0.997	0.998	1.0	1.0	1.0	0.41	0.41	0.51
# 9 Sequence 1	11:06	11:20	10:50	0.30	7.37	7.33	0.977	0.996	0.998	1.0	1.0	1.0	0.14	0.44	0.67
# 9 Sequence 2	11:48	12:01	11:33	7.32	7.43	7.37	0.868	0.994	0.995	1.0	1.0	1.0	0.08	0.31	0.37
# 9 Sequence 3	12:27	12:37	12:16	7.32	7.47	7.49	0.784	0.992	0.994	1.0	1.0	1.0	0.07	0.23	0.32
# 8 Sequence 1	11:55	11:06	11:22	7.48	7.43	7.44	0.998	0.999	0.999	1.0	1.0	1.0	0.70	0.91	0.85
# 8 Sequence 2	12:08	12:34	12:23	7.46	7.45	7.44	0.998	0.998	0.999	1.0	1.0	1.0	0.63	0.55	0.71
# 8 Sequence 3	13:15	12:47	13:00	7.47	7.43	7.47	0.997	0.998	0.998	1.0	1.0	1.0	0.42	0.61	0.62
# 7 Sequence 1	11:45	11:25	12:28	7.41	7.43	7.52	0.911	0.999	0.996	1.0	1.0	1.0	0.09	0.77	0.36
# 7 Sequence 2	13:06	12:52	12:41	7.47	7.59	7.55	0.867	0.996	0.996	1.0	1.0	1.0	0.07	0.31	0.34
# 7 Sequence 3	13:16	13:28	13:43	7.43	7.62	7.61	0.819	0.991	0.969	1.0	1.0	1.0	0.07	0.19	0.11
# 6 Sequence 1	10:45	10:00	10:28	7.53	7.35	7.67	0.997	0.997	0.998	1.0	1.0	1.0	0.39	0.48	0.43
# 6 Sequence 2	11:14	11:26	11:00	7.52	0.48	7.59	0.997	0.997	0.997	1.0	1.0	1.0	0.39	0.41	0.41
# 6 Sequence 3	12:05	11:52	11:40	7.41	7.44	7.46	0.998	0.994	0.995	1.0	1.0	1.0	0.21	0.30	0.33
# 4 Sequence 1	10:25	11:05	10:45	7.40	7.51	7.45	0.991	0.988	0.989	1.0	1.0	1.0	0.24	0.19	0.21
# 4 Sequence 2	11:22	11:55	11:37	7.44	7.55	7.47	0.911	0.986	0.880	1.0	1.0	1.0	0.09	0.17	0.08
# 4 Sequence 3	12:28	12:15	12:42	7.50	7.59	7.49	0.765	0.987	0.673	1.0	1.0	1.0	0.06	0.16	0.05
# 3 Sequence 1	11:47	11:15	11:28	7.43	7.45	7.50	0.909	0.995	0.929	1.0	0.5	0.5	0.08	0.67	0.18
# 3 Sequence 2	12:55	12:00	12:20	7.35	7.47	7.39	0.599	0.960	0.699	1.0	1.0	1.0	0.05	0.11	0.06
# 2 Sequence 1	10:55	11:10	11:27	7.36	7.43	7.73	0.973	0.976	0.995	1.0	0.5	0.5	0.15	0.31	0.45
# 2 Sequence 2	11:47	11:57	12:11	7.53	7.55	7.52	0.876	0.985	0.970	1.0	0.5	0.5	0.07	0.33	0.25
# 2 Sequence 3	12:22	12:33	12:44	7.49	7.56	7.51	0.897	0.982	0.937	1.0	0.5	0.5	0.08	0.30	0.19
# 2 Sequence 4	12:56	13:09	13:19	7.46	7.56	7.52	0.849	0.960	0.922	1.0	0.5	0.5	0.07	0.21	0.17
# 1 Sequence 1	12:05	11:30	13:00	7.48	7.43	7.65				0.5	0.5	0.5	1.21	0.92	0.25
# 1 Sequence 2	12:45	13:34	14:10	7.43	7.52	7.70				1.0	0.5	0.5	0.14	0.88	0.27
# 1 Sequence 3	14:35	13:45	14:28	7.52	7.58	7.58				0.5	0.5	0.5	0.33	0.95	0.29

Table 2b. Complete Physiological Experimental Data.

	Time CV	Time UHFJV	Time CJV	AA GRAD CV	AA GRAD UHFJV	AA GRAD CJV	O2 Cont. CV	O2 Cont UHFJV	O2 Cont. CJV	O2 Carry CV	O2 Carry UHFJV	O2 Carry CJV	Flow/BPF CV	Flow/BPF UHFJV	Flow/BPF CJV
#11 Sequence 1	10:21	10:06	09:54	352.55	321.18	339.13	17.63	17.78	17.71	188.59	172.63	231.45	4448	3168	3089
#11 Sequence 2	10:32	10:44	10:53	375.70	323.88	301.00	17.52	17.78	17.88	182.43	161.78	176.97	3762	2030	3346
#11 Sequence 3	11:09	11:21	11:31	424.60	331.10	376.15	17.40	17.71	17.63	174.73	172.88	190.35	4805	2772	3326
#10 Sequence 1	10:30	09:50	10:15	504.48	62.23	296.13	17.04	18.55	17.83	125.60	150.10	139.60	4497	1093	1774
#10 Sequence 2	10:56	10:45	11:07	498.15	280.85	304.38	17.05	17.85	17.81	118.30	142.44	155.99	5333	1604	928
#10 Sequence 3	11:18	11:33	11:43	396.83	400.88	333.55	17.47	17.48	17.72	146.94	140.72	157.93	4541	1277	1901
# 9 Sequence 1	11:06	11:20	10:50	564.18	370.65	220.0	16.58	17.53	18.03	143.42	153.90	161.90	12605	2667	3960
# 9 Sequence 2	11:48	12:01	11:33	607.23	463.95	424.25	14.65	17.23	17.36	124.24	150.75	151.21	12978	3663	4699
# 9 Sequence 3	12:27	12:37	12:16	614.80	521.10	456.75	13.22	17.04	17.25	110.91	142.46	149.24	13127	4752	4950
# 8 Sequence 1	11:55	11:06	11:22	202.03	62.98	100.85	16.93	18.53	18.41	165.22	162.34	171.41	3950	804	2394
# 8 Sequence 2	12:08	12:34	12:23	248.75	296.00	194.55	17.95	17.78	18.12	170.30	165.04	178.45	8092	603	1021
# 8 Sequence 3	13:15	12:47	13:00	394.25	258.50	252.75	17.50	17.91	17.95	170.78	173.35	217.32	5315	1598	1277
# 7 Sequence 1	11:45	11:25	12:28	605.88	151.00	431.50	15.38	18.28	17.38	178.25	183.48	174.12	10545	3335	6810
# 7 Sequence 2	13:06	12:52	12:41	626.00	473.95	450.00	14.61	17.27	17.34	161.30	185.87	166.34	5260	3299	6203
# 7 Sequence 3	13:16	13:28	13:43	626.75	559.58	614.25	13.80	16.93	16.39	135.35	206.05	182.56	7638	3060	7806
# 6 Sequence 1	10:45	10:00	10:28	411.05	336.08	388.23	17.43	17.48	17.57	147.84	177.99	177.59	3073	1300	1386
# 6 Sequence 2	11:14	11:26	11:00	409.03	396.63	399.03	17.45	17.47	17.50	171.57	183.58	174.27	2095	571	980
# 6 Sequence 3	12:05	11:52	11:40	524.23	461.78	444.23	17.07	17.20	17.28	170.90	174.61	173.80	2304	277	1230
# 4 Sequence 1	10:25	11:05	10:45	502.43	551.00	533.15	17.03	16.87	16.93	191.40	168.57	194.21	3388	891	1832
# 4 Sequence 2	11:22	11:55	11:37	614.03	565.93	618.55	15.37	16.79	14.84	146.05	181.21	140.52	3972	1392	1594
# 4 Sequence 3	12:28	12:15	12:42	633.50	572.60	637.38	12.88	16.81	11.32	126.70	167.58	120.16	4406	1893	1386
# 3 Sequence 1	11:47	11:15	11:28	617.43	105.75	261.03	15.34	17.25	15.68	142.04	136.48	148.15	2385	446	1871
# 3 Sequence 2	12:55	12:00	12:20	652.00	605.80	626.65	10.09	16.25	11.77	40.66	90.51	73.59	2325	2153	2218
# 2 Sequence 1	10:55	11:10	11:27	563.15	220.08	188.53	16.54	16.58	17.07	130.65	141.94	120.19	4681	930	1162
# 2 Sequence 2	11:47	11:57	12:11	632.28	219.90	242.55	14.76	16.76	16.43	115.54	118.84	127.65	5378	891	1608
# 2 Sequence 3	12:22	12:33	12:44	626.73	231.28	263.45	15.12	16.68	15.82	107.66	118.27	108.81	4107	683	1742
# 2 Sequence 4	12:56	13:09	13:19	629.35	261.03	265.30	14.30	16.22	15.55	99.12	95.72	95.80	2962	1420	3137
# 1 Sequence 1	12:05	11:30	13:00	-67.50	25.75	245.78							3140	297	3406
# 1 Sequence 2	12:45	13:34	14:10	571.88	37.25	243.50							6356	725	2693
# 1 Sequence 3	14:35	13:45	14:28	218.70	17.13	230.75							7583	668	2396

Table 2c. Complete Physiological Experimental Data.

row	pO2	pCO2	AA RATIO	AA GRAD	Flow/BPF	CO-MEAN	PCW	pH	SAT	ventls	amls	sqn	FIO2	O2 Cont.	O2 Carry	Time
1	321.2	31.4	0.4767347	352.550	4448	10.70	14	7.36	0.997	CV	11	1	1.0	17.63	188.59	27
2	293.8	34.8	0.4388350	375.700	3762	10.41	10	7.33	0.996	CV	11	2	1.0	17.52	182.43	38
3	254.9	26.8	0.3751288	424.600	4805	10.04	12	7.41	0.996	CV	11	3	1.0	17.40	174.73	75
4	165.4	34.5	0.2469117	504.475	4497	7.37	11	7.42	0.991	CV	10	1	1.0	17.04	125.60	40
5	166.6	38.6	0.2506205	498.150	5333	6.94	12	7.40	0.991	CV	10	2	1.0	17.05	118.30	66
6	271.8	35.5	0.4065059	396.825	4541	8.41	15	7.45	0.997	CV	10	3	1.0	17.47	146.94	88
7	91.7	45.7	0.1398132	564.175	12605	8.65	15	0.30	0.977	CV	9	1	1.0	16.58	143.42	16
8	55.9	39.9	0.0842978	607.225	12978	8.48	12	7.32	0.868	CV	9	2	1.0	14.65	124.24	63
9	45.7	42.0	0.0691900	614.800	13127	8.39	16	7.32	0.784	CV	9	3	1.0	13.22	110.91	97
10	462.1	39.1	0.6958027	202.025	3950	9.76	16	7.48	0.998	CV	8	1	1.0	16.93	165.22	49
11	419.0	36.2	0.6274803	248.750	8092	9.49	18	7.46	0.998	CV	8	2	1.0	17.95	170.30	62
12	280.0	31.0	0.4152762	394.250	5315	9.76	10	7.47	0.997	CV	8	3	1.0	17.50	170.78	129
13	59.5	38.1	0.0894233	605.875	10545	11.59	17	7.41	0.911	CV	7	1	1.0	15.38	178.25	20
14	48.0	31.2	0.0712166	626.000	5260	11.04	16	7.47	0.867	CV	7	2	1.0	14.61	161.30	101
15	44.0	33.8	0.0655982	626.750	7638	9.81	18	7.43	0.819	CV	7	3	1.0	13.80	135.35	111
16	259.2	34.2	0.3867214	411.050	3073	8.48	12	7.53	0.997	CV	6	1	1.0	17.43	147.84	45
17	265.6	30.7	0.3937002	409.025	2095	9.83	11	7.52	0.997	CV	6	2	1.0	17.45	171.57	74
18	137.4	41.1	0.2076705	524.225	2304	10.01	12	7.41	0.998	CV	6	3	1.0	17.07	170.90	125
19	160.7	39.9	0.2423374	502.425	3388	11.24	16	7.40	0.991	CV	4	1	1.0	17.03	191.40	0
20	57.6	33.1	0.0857621	614.025	3972	9.50	19	7.44	0.911	CV	4	2	1.0	15.37	146.05	57
21	37.5	33.6	0.0558867	633.500	4406	9.84	15	7.50	0.765	CV	4	3	1.0	12.88	126.70	123
22	57.2	30.7	0.0847878	617.425	2385	9.26	10	7.43	0.909	CV	3	1	1.0	15.34	142.04	32
23	31.5	23.6	0.0460863	652.000	2325	4.03	10	7.35	0.599	CV	3	2	1.0	10.09	40.66	80
24	99.6	40.2	0.1502829	563.150	4681	7.90	10	7.36	0.973	CV	2	1	1.0	16.54	130.65	0
25	46.6	27.3	0.0686430	632.275	5378	7.83	23	7.53	0.876	CV	2	2	1.0	14.76	115.54	52
26	51.4	27.9	0.0757972	626.725	4107	7.12	15	7.49	0.897	CV	2	3	1.0	15.12	107.66	87
27	45.9	30.2	0.0679748	629.350	2962	6.93	8	7.46	0.849	CV	2	4	1.0	14.30	99.12	121
28	282.0	33.6	0.8966614	32.500	3140	6.08	8	7.48	0.000	CV	1	1	0.5	0.00	0.00	35
29	91.0	40.1	0.1372808	571.875	6356	6.19	10	7.43	0.000	CV	1	2	1.0	0.00	0.00	75
30	105.3	26.0	0.3250000	218.700	7583	6.04	16	7.52	0.000	CV	1	3	0.5	0.00	0.00	185
31	342.5	25.1	0.5024757	339.125	3089	13.07	12	7.47	0.998	CJV	11	1	1.0	17.71	231.45	0
32	391.0	16.8	0.5650289	301.000	3346	9.90	13	7.56	0.999	CJV	11	2	1.0	17.88	176.97	59
33	315.6	17.0	0.4562342	376.150	3326	10.80	14	7.58	0.998	CJV	11	3	1.0	17.63	190.35	97
34	381.5	28.3	0.5629958	296.125	1774	7.83	11	7.47	0.998	CJV	10	1	1.0	17.83	139.60	25
35	374.5	27.3	0.5516479	304.375	928	8.76	14	7.51	0.998	CJV	10	2	1.0	17.81	155.99	77
36	347.7	25.4	0.5103853	333.550	1901	8.91	12	7.55	0.998	CJV	10	3	1.0	17.72	157.93	113
37	445.8	37.7	0.6694950	220.075	3960	8.98	15	7.33	0.998	CJV	9	1	1.0	18.03	161.90	0
38	246.5	33.8	0.3674991	424.250	4699	8.71	15	7.37	0.995	CJV	9	2	1.0	17.36	151.21	43
39	217.0	31.4	0.3220779	456.750	4950	8.65	18	7.49	0.994	CJV	9	3	1.0	17.25	149.24	86
40	563.9	38.6	0.8482888	100.850	2394	9.31	22	7.44	0.999	CJV	8	1	1.0	18.41	171.41	16
41	468.7	39.8	0.7066717	194.550	1021	9.85	17	7.44	0.999	CJV	8	2	1.0	18.12	178.45	77
42	419.0	33.0	0.6237440	252.750	1277	12.11	12	7.47	0.998	CJV	8	3	1.0	17.95	217.32	114
43	246.5	28.0	0.3635693	431.500	6810	10.02	20	7.52	0.996	CJV	7	1	1.0	17.38	174.12	123
44	236.0	21.6	0.3440233	450.000	6203	9.59	22	7.55	0.996	CJV	7	2	1.0	17.34	166.34	136
45	72.5	21.0	0.1055697	614.250	7806	11.14	15	7.61	0.969	CJV	7	3	1.0	16.39	182.56	198

Table 3. Physiological and Flow Data - Unbalanced Design.

row	pO2	pCO2	AA RATIO	AA GRAD	Flow/BPF	CO-MEAN	PCW	pH	SAT	ventls	amls	sqn	FIO2	O2 Cont.	O2 Carry	Time
46	296.4	22.7	0.4329377	388.225	1386	10.11	12	7.67	0.998	CJV	6	1	1.0	17.57	177.59	28
47	279.6	27.5	0.4120096	399.025	980	9.96	11	7.59	0.997	CJV	6	2	1.0	17.50	174.27	60
48	219.4	39.5	0.3306084	444.225	1230	10.06	10	7.46	0.995	CJV	6	3	1.0	17.28	173.80	100
49	140.6	31.4	0.2086827	533.150	1832	11.47	29	7.45	0.989	CJV	4	1	1.0	16.93	194.21	20
50	51.7	34.2	0.0771354	618.550	1594	9.47	18	7.47	0.880	CJV	4	2	1.0	14.84	140.52	72
51	32.0	34.9	0.0478058	637.375	1386	10.61	16	7.49	0.673	CJV	4	3	1.0	11.32	120.16	137
52	58.6	29.5	0.1833399	261.025	1871	9.45	12	7.50	0.929	CJV	3	1	0.5	15.68	148.15	13
53	37.1	39.4	0.0558945	626.650	2218	6.25	12	7.39	0.699	CJV	3	2	1.0	11.77	73.59	65
54	153.6	11.5	0.4489587	188.525	1162	7.04	9	7.73	0.995	CJV	2	1	0.5	17.07	120.19	32
55	80.2	27.0	0.2484895	242.550	1608	7.77	16	7.52	0.970	CJV	2	2	0.5	16.43	127.65	76
56	60.3	26.2	0.1862548	263.450	1742	6.88	10	7.51	0.937	CJV	2	3	0.5	15.82	108.81	109
57	55.7	28.4	0.1735202	265.300	3137	6.16	8	7.52	0.922	CJV	2	4	0.5	15.55	95.80	144
58	81.6	23.3	0.2492554	245.775	3406	7.50	10	7.65	0.000	CJV	1	1	0.5	0.00	0.00	90
59	90.0	18.4	0.2698651	243.500	2693	7.65	10	7.70	0.000	CJV	1	2	0.5	0.00	0.00	160
60	93.5	25.8	0.2883577	230.750	2396	8.18	12	7.58	0.000	CJV	1	3	0.5	0.00	0.00	178
61	365.2	21.3	0.5320707	321.175	3168	9.71	0	7.47	0.998	UHFJV	11	1	1.0	17.78	172.63	12
62	365.0	19.3	0.5298494	323.875	2030	9.10	10	7.47	0.998	UHFJV	11	2	1.0	17.78	161.78	50
63	354.9	21.6	0.5173469	331.100	2772	9.76	14	7.50	0.996	UHFJV	11	3	1.0	17.71	172.88	87
64	609.9	32.7	0.9074205	62.225	1093	8.09	12	7.38	0.999	UHFJV	10	1	1.0	18.55	150.10	0
65	387.9	35.4	0.5800374	280.850	1604	7.98	15	7.43	0.998	UHFJV	10	2	1.0	17.85	142.44	55
66	274.5	30.1	0.4064409	400.875	1277	8.05	13	7.45	0.997	UHFJV	10	3	1.0	17.48	140.72	103
67	295.1	37.8	0.4432595	370.650	2667	8.78	12	7.37	0.996	UHFJV	9	1	1.0	17.53	153.90	30
68	209.3	31.8	0.3108801	463.950	3663	8.75	14	7.43	0.994	UHFJV	9	2	1.0	17.23	150.75	71
69	159.4	26.0	0.2342395	521.100	4752	8.36	18	7.47	0.992	UHFJV	9	3	1.0	17.04	142.46	107
70	602.9	37.7	0.9054252	62.975	804	8.76	18	7.43	0.999	UHFJV	8	1	1.0	18.53	162.34	0
71	367.0	40.0	0.5535445	296.000	603	9.28	14	7.45	0.998	UHFJV	8	2	1.0	17.78	165.04	88
72	407.0	38.0	0.6115702	258.500	1598	9.68	12	7.43	0.998	UHFJV	8	3	1.0	17.91	173.35	101
73	520.0	33.6	0.7749627	151.000	3335	10.04	19	7.43	0.999	UHFJV	7	1	1.0	18.28	183.48	0
74	213.3	20.6	0.3103674	473.950	3299	10.76	20	7.59	0.996	UHFJV	7	2	1.0	17.27	185.87	87
75	129.3	19.3	0.1876973	559.575	3060	12.17	19	7.62	0.991	UHFJV	7	3	1.0	16.93	206.05	125
76	307.8	55.3	0.4780431	336.075	1300	10.18	13	7.35	0.997	UHFJV	6	1	1.0	17.48	177.99	0
77	270.0	37.1	0.4050253	396.625	571	10.51	13	0.48	0.997	UHFJV	6	2	1.0	17.47	183.58	86
78	201.1	40.1	0.3033754	461.775	277	10.15	14	7.44	0.994	UHFJV	6	3	1.0	17.20	174.61	112
79	127.0	28.0	0.1873156	551.000	891	9.99	19	7.51	0.988	UHFJV	4	1	1.0	16.87	168.57	40
80	112.2	27.9	0.1654562	565.925	1392	10.79	15	7.55	0.986	UHFJV	4	2	1.0	16.79	181.21	90
81	111.4	23.2	0.1628655	572.600	1893	9.97	17	7.59	0.987	UHFJV	4	3	1.0	16.81	167.58	110
82	212.0	31.0	0.6671912	105.750	446	7.91	10	7.45	0.995	UHFJV	3	1	0.5	17.25	136.48	0
83	76.2	24.8	0.1117302	605.800	2153	5.57	15	7.47	0.960	UHFJV	3	2	1.0	16.25	90.51	45
84	97.3	31.3	0.3065774	220.075	930	8.56	10	7.43	0.976	UHFJV	2	1	0.5	16.58	141.94	15
85	107.1	23.6	0.3275229	219.900	891	7.09	12	7.55	0.985	UHFJV	2	2	0.5	16.76	118.84	62
86	97.1	22.5	0.2956985	231.275	683	7.09	11	7.56	0.982	UHFJV	2	3	0.5	16.68	118.27	98
87	68.1	21.9	0.2069123	261.025	1420	5.90	6	7.56	0.960	UHFJV	2	4	0.5	16.22	95.72	134
88	282.0	39.0	0.9163282	25.750	297	5.48	10	7.43	0.000	UHFJV	1	1	0.5	0.00	0.00	0
89	279.0	32.2	0.8822134	37.250	725	6.19	15	7.52	0.000	UHFJV	1	2	0.5	0.00	0.00	124
90	302.0	29.9	0.9463376	17.125	668	5.92	17	7.58	0.000	UHFJV	1	3	0.5	0.00	0.00	135

Table 3. Continued.

row	pO2	pCO2	AA RATIO	AA GRAD	Flow/BPF	CO-MEAN	PCW	pH	SAT	ventls	amls	sqn	FIO2	O2 Cont	O2 Carry	Time
1	321.2	31.4	0.4767350	352.550	4448	10.70	14	7.36	0.997	CV	11	1	1.0	17.63	188.60	27
2	293.8	34.8	0.4388350	375.700	3762	10.41	10	7.33	0.996	CV	11	2	1.0	17.52	182.43	38
3	254.9	26.8	0.3751290	424.600	4805	10.04	12	7.41	0.996	CV	11	3	1.0	17.40	174.73	75
4	165.4	34.5	0.2469120	504.475	4497	7.37	11	7.42	0.991	CV	10	1	1.0	17.04	125.60	40
5	166.6	38.6	0.2506210	498.150	5333	6.94	12	7.40	0.991	CV	10	2	1.0	17.05	118.30	66
6	271.8	35.5	0.4065060	396.825	4541	8.41	15	7.45	0.997	CV	10	3	1.0	17.47	146.94	88
7	91.7	45.7	0.1398130	564.175	12605	8.65	15	0.30	0.977	CV	9	1	1.0	16.58	143.42	16
8	55.9	39.9	0.0842978	607.225	12978	8.48	12	7.32	0.868	CV	9	2	1.0	14.65	124.25	63
9	45.7	42.0	0.0691900	614.800	13127	8.39	16	7.32	0.784	CV	9	3	1.0	13.22	110.91	97
10	462.1	39.1	0.6958030	202.025	3950	9.76	16	7.48	0.998	CV	8	1	1.0	16.93	165.23	49
11	419.0	36.2	0.6274800	248.750	8092	9.49	18	7.46	0.998	CV	8	2	1.0	17.95	170.30	62
12	280.0	31.0	0.4152760	394.250	5315	9.76	10	7.47	0.997	CV	8	3	1.0	17.50	170.78	129
13	59.5	38.1	0.0894233	605.875	10545	11.59	17	7.41	0.911	CV	7	1	1.0	15.38	178.25	20
14	48.0	31.2	0.0712166	626.000	5260	11.04	16	7.47	0.867	CV	7	2	1.0	14.61	161.30	101
15	44.0	33.8	0.0655982	626.750	7638	9.81	18	7.43	0.819	CV	7	3	1.0	13.80	135.35	111
16	259.2	34.2	0.3867210	411.050	3073	8.48	12	7.53	0.997	CV	6	1	1.0	17.43	147.84	45
17	265.6	30.7	0.3937000	409.025	2095	9.83	11	7.52	0.997	CV	6	2	1.0	17.45	171.57	74
18	137.4	41.1	0.2076710	524.225	2304	10.01	12	7.41	0.998	CV	6	3	1.0	17.07	170.90	125
19	160.7	39.9	0.2423370	502.425	3388	11.24	16	7.40	0.991	CV	4	1	1.0	17.03	191.40	0
20	57.6	33.1	0.0857621	614.025	3972	9.50	19	7.44	0.911	CV	4	2	1.0	15.37	146.05	57
21	37.5	33.6	0.0558867	633.500	4406	9.84	15	7.50	0.765	CV	4	3	1.0	12.88	126.70	123
22	99.6	40.2	0.1502830	563.150	4681	7.90	10	7.36	0.973	CV	2	1	1.0	16.54	130.65	0
23	46.6	27.3	0.0686430	632.275	5378	7.83	23	7.53	0.876	CV	2	2	1.0	14.76	115.54	52
24	51.4	27.9	0.0757972	626.725	4107	7.12	15	7.49	0.897	CV	2	3	1.0	15.12	107.66	87
25	282.0	33.6	0.8966610	32.500	3140	6.08	8	7.48	0.000	CV	1	1	0.5	0.00	0.00	35
26	91.0	40.1	0.1372810	571.875	6356	6.19	10	7.43	0.000	CV	1	2	1.0	0.00	0.00	75
27	105.3	26.0	0.3250000	218.700	7583	6.04	16	7.52	0.000	CV	1	3	0.5	0.00	0.00	185
28	342.5	25.1	0.5024760	339.125	3089	13.07	12	7.47	0.998	CJV	11	1	1.0	17.71	231.45	0
29	391.0	16.8	0.5650290	301.000	3346	9.90	13	7.56	0.999	CJV	11	2	1.0	17.88	176.97	59
30	315.6	17.0	0.4562340	376.150	3326	10.80	14	7.58	0.998	CJV	11	3	1.0	17.63	190.35	97
31	381.5	28.3	0.5629960	296.125	1774	7.83	11	7.47	0.998	CJV	10	1	1.0	17.83	139.60	25
32	374.5	27.3	0.5516480	304.375	928	8.76	14	7.51	0.998	CJV	10	2	1.0	17.81	155.99	77
33	347.7	25.4	0.5103850	333.550	1901	8.91	12	7.55	0.998	CJV	10	3	1.0	17.72	157.93	113
34	445.8	37.7	0.6694950	220.075	3960	8.98	15	7.33	0.998	CJV	9	1	1.0	18.03	161.90	0
35	246.5	33.8	0.3674990	424.250	4699	8.71	15	7.37	0.995	CJV	9	2	1.0	17.36	151.21	43
36	217.0	31.4	0.3220780	456.750	4950	8.65	18	7.49	0.994	CJV	9	3	1.0	17.25	149.24	86
37	563.9	38.6	0.8482890	100.850	2394	9.31	22	7.44	0.999	CJV	8	1	1.0	18.41	171.41	16
38	468.7	39.8	0.7066720	194.550	1021	9.85	17	7.44	0.999	CJV	8	2	1.0	18.12	178.45	77
39	419.0	33.0	0.6237440	252.750	1277	12.11	12	7.47	0.998	CJV	8	3	1.0	17.95	217.32	114
40	246.5	28.0	0.3635690	431.500	6810	10.02	20	7.52	0.996	CJV	7	1	1.0	17.38	174.12	123
41	236.0	21.6	0.3440230	450.000	6203	9.59	22	7.55	0.996	CJV	7	2	1.0	17.34	166.34	136
42	72.5	21.0	0.1055700	614.250	7806	11.14	15	7.61	0.969	CJV	7	3	1.0	16.39	182.56	198
43	296.4	22.7	0.4329380	388.225	1386	10.11	12	7.67	0.998	CJV	6	1	1.0	17.57	177.59	28
44	279.6	27.5	0.4120100	399.025	980	9.96	11	7.59	0.997	CJV	6	2	1.0	17.50	174.27	60
45	219.4	39.5	0.3306080	444.225	1230	10.06	10	7.46	0.995	CJV	6	3	1.0	17.28	173.80	100

Table 4. Physiological and Flow Data - Balanced Design.

row	pO2	pCO2	AA RATIO	AA GRAD	Flow/BPF	CO-MEAN	PCW	pH	SAT	ventls	amls	sqn	FIO2	O2 Cont.	O2 Carry	Time
46	140.6	31.4	0.2086830	533.150	1832	11.47	29	7.45	0.989	CJV	4	1	1.0	16.93	194.21	20
47	51.7	34.2	0.0771354	618.550	1594	9.47	18	7.47	0.880	CJV	4	2	1.0	14.84	140.52	72
48	32.0	34.9	0.0478058	637.375	1386	10.61	16	7.49	0.673	CJV	4	3	1.0	11.32	120.16	137
49	153.6	11.5	0.4489590	188.525	1162	7.04	9	7.73	0.995	CJV	2	1	0.5	17.07	120.19	32
50	80.2	27.0	0.2484900	242.550	1608	7.77	16	7.52	0.970	CJV	2	2	0.5	16.43	127.65	76
51	60.3	26.2	0.1862550	263.450	1742	6.88	10	7.51	0.937	CJV	2	3	0.5	15.82	108.82	109
52	81.6	23.3	0.2492550	245.775	3406	7.50	10	7.65	0.000	CJV	1	1	0.5	0.00	0.00	90
53	90.0	18.4	0.2698650	243.500	2693	7.65	10	7.70	0.000	CJV	1	2	0.5	0.00	0.00	160
54	93.5	25.8	0.2883580	230.750	2396	8.18	12	7.58	0.000	CJV	1	3	0.5	0.00	0.00	178
55	365.2	21.3	0.5320710	321.175	3168	9.71	0	7.47	0.998	UHFJV	11	1	1.0	17.78	172.63	12
56	365.0	19.3	0.5298490	323.875	2030	9.10	10	7.47	0.998	UHFJV	11	2	1.0	17.78	161.78	50
57	354.9	21.6	0.5173470	331.100	2772	9.76	14	7.50	0.996	UHFJV	11	3	1.0	17.71	172.88	87
58	609.9	32.7	0.9074200	62.225	1093	8.09	12	7.38	0.999	UHFJV	10	1	1.0	18.55	150.10	0
59	387.9	35.4	0.5800370	280.850	1604	7.98	15	7.43	0.998	UHFJV	10	2	1.0	17.85	142.44	55
60	274.5	30.1	0.4064410	400.875	1277	8.05	13	7.45	0.997	UHFJV	10	3	1.0	17.48	140.72	103
61	295.1	37.8	0.4432590	370.650	2667	8.78	12	7.37	0.996	UHFJV	9	1	1.0	17.53	153.90	30
62	209.3	31.8	0.3108800	463.950	3663	8.75	14	7.43	0.994	UHFJV	9	2	1.0	17.23	150.75	71
63	159.4	26.0	0.2342400	521.100	4752	8.36	18	7.47	0.992	UHFJV	9	3	1.0	17.04	142.46	107
64	602.9	37.7	0.9054250	62.975	804	8.76	18	7.43	0.999	UHFJV	8	1	1.0	18.53	162.34	0
65	367.0	40.0	0.5535440	296.000	603	9.28	14	7.45	0.998	UHFJV	8	2	1.0	17.78	165.04	88
66	407.0	38.0	0.6115700	258.500	1598	9.68	12	7.43	0.998	UHFJV	8	3	1.0	17.91	173.35	101
67	520.0	33.6	0.7749630	151.000	3335	10.04	19	7.43	0.999	UHFJV	7	1	1.0	18.28	183.48	0
68	213.3	20.6	0.3103670	473.950	3299	10.76	20	7.59	0.996	UHFJV	7	2	1.0	17.27	185.87	87
69	129.3	19.3	0.1876970	559.575	3060	12.17	19	7.62	0.991	UHFJV	7	3	1.0	16.93	206.05	125
70	307.8	55.3	0.4780430	336.075	1300	10.18	13	7.35	0.997	UHFJV	6	1	1.0	17.48	177.99	0
71	270.0	37.1	0.4050250	396.625	571	10.51	13	0.48	0.997	UHFJV	6	2	1.0	17.47	183.58	86
72	201.1	40.1	0.3033750	461.775	277	10.15	14	7.44	0.994	UHFJV	6	3	1.0	17.20	174.61	112
73	127.0	28.0	0.1873160	551.000	891	9.99	19	7.51	0.988	UHFJV	4	1	1.0	16.87	168.57	40
74	112.2	27.9	0.1654560	565.925	1392	10.79	15	7.55	0.986	UHFJV	4	2	1.0	16.79	181.21	90
75	111.4	23.2	0.1628650	572.600	1893	9.97	17	7.59	0.987	UHFJV	4	3	1.0	16.81	167.58	110
76	97.3	31.3	0.3065770	220.075	930	8.56	10	7.43	0.976	UHFJV	2	1	0.5	16.58	141.94	15
77	107.1	23.6	0.3275230	219.900	891	7.09	12	7.55	0.985	UHFJV	2	2	0.5	16.76	118.84	62
78	97.1	22.5	0.2956990	231.275	683	7.09	11	7.56	0.982	UHFJV	2	3	0.5	16.68	118.27	98
79	282.0	39.0	0.9163280	25.750	297	5.48	10	7.43	0.000	UHFJV	1	1	0.5	0.00	0.00	0
80	279.0	32.2	0.8822130	37.250	725	6.19	15	7.52	0.000	UHFJV	1	2	0.5	0.00	0.00	124
81	302.0	29.9	0.9463380	17.125	668	5.92	17	7.58	0.000	UHFJV	1	3	0.5	0.00	0.00	135

Table 4. Continued.

Tests for Randomness

Data: ord

Median = 2 based on 90 observations.
Number of runs above and below median = 49
Expected number = 41
Large sample test statistic Z = 1.79141
Two-tailed probability of equaling or exceeding Z = 0.0732279

Number of runs up and down = 60
Expected number = 53
Large sample test statistic Z = 1.74344
Two-tailed probability of equaling or exceeding Z = 0.0812572

NOTE: 10 adjacent values ignored.

Table 5. Test for Randomness.

Table of means for a/A Ratio

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
amls						
1	9	.5456999	.1166663	.0420686	.4599889	.6314108
2	9	.2342474	.0418159	.0420686	.1485364	.3199583
4	9	.1370274	.0238598	.0420686	.0513165	.2227384
6	9	.3722323	.0268131	.0420686	.2865214	.4579433
7	9	.2569363	.0761057	.0420686	.1712254	.3426473
8	9	.6653114	.0492771	.0420686	.5796005	.7510224
9	9	.2934169	.0636403	.0420686	.2077059	.3791278
10	9	.4914407	.0668974	.0420686	.4057297	.5771516
11	9	.4881894	.0193615	.0420686	.4024785	.5739004
ventls						
CV	27	.2769844	.0422934	.0242883	.2274992	.3264696
CJV	27	.3962989	.0379749	.0242883	.3468136	.4457841
UHFJV	27	.4882173	.0488772	.0242883	.4387321	.5377026
sqn						
1	27	.4838056	.0506327	.0242883	.4343203	.5332908
2	27	.3616704	.0412701	.0242883	.3121852	.4111557
3	27	.3160246	.0404590	.0242883	.2665394	.3655098
amls by ventls						
1 CV	3	.4529807	.2283629	.0728649	.3045250	.6014364
1 CJV	3	.2691593	.0112936	.0728649	.1207036	.4176150
1 UHFJ	3	.9149597	.0185239	.0728649	.7665040	1.0634154
2 CV	3	.0982411	.0261028	.0728649	-.0502146	.2466968
2 CJV	3	.2945680	.0792585	.0728649	.1461123	.4430237
2 UHFJ	3	.3099330	.0093388	.0728649	.1614773	.4583887
4 CV	3	.1279953	.0578177	.0728649	-.0204604	.2764510
4 CJV	3	.1112081	.0494674	.0728649	-.0372476	.2596638
4 UHFJ	3	.1718790	.0077547	.0728649	.0234233	.3203347
6 CV	3	.3293640	.0608798	.0728649	.1809083	.4778197
6 CJV	3	.3918520	.0312123	.0728649	.2433963	.5403077
6 UHFJ	3	.3954810	.0506476	.0728649	.2470253	.5439367
7 CV	3	.0754127	.0071906	.0728649	-.0730430	.2238684
7 CJV	3	.2710540	.0829342	.0728649	.1225983	.4195097
7 UHFJ	3	.4243423	.1788511	.0728649	.2758866	.5727980
8 CV	3	.5795197	.0844571	.0728649	.4310640	.7279754
8 CJV	3	.7262350	.0655544	.0728649	.5777793	.8746907
8 UHFJ	3	.6901797	.1089184	.0728649	.5417240	.8386354
9 CV	3	.0977669	.0214706	.0728649	-.0506888	.2462226
9 CJV	3	.4530240	.1090268	.0728649	.3045683	.6014797
9 UHFJ	3	.3294597	.0610495	.0728649	.1810040	.4779154
10 CV	3	.3013463	.0525907	.0728649	.1528906	.4498020
10 CJV	3	.5416763	.0159849	.0728649	.3932206	.6901320
10 UHFJ	3	.6312993	.1468739	.0728649	.4828436	.7797550
11 CV	3	.4302330	.0296448	.0728649	.2817773	.5786887
11 CJV	3	.5079130	.0315238	.0728649	.3594573	.6563687
11 UHFJ	3	.5264223	.0045828	.0728649	.3779666	.6748780
Total	81	.3871669	.0140229	.0140229	.3585966	.4157372

Table 6a. Analysis of Variance Table for a/A Ratio.
Three Factor Balanced Design.

Table of means for a/A Ratio

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
amls by sqn							
1	1	3	.6874147	.2191534	.0728649	.5389590	.8358704
1	2	3	.4297863	.2294283	.0728649	.2813306	.5782420
1	3	3	.5198987	.2134819	.0728649	.3714430	.6683544
2	1	3	.3019397	.0862515	.0728649	.1534840	.4503954
2	2	3	.2148853	.0765978	.0728649	.0664296	.3633410
2	3	3	.1859171	.0634804	.0728649	.0374614	.3343728
4	1	3	.2127787	.0160147	.0728649	.0643230	.3612344
4	2	3	.1094512	.0281129	.0728649	-.0390045	.2579069
4	3	3	.0888525	.0370797	.0728649	-.0596032	.2373082
6	1	3	.4325673	.0263630	.0728649	.2841116	.5810230
6	2	3	.4035783	.0053349	.0728649	.2551226	.5520340
6	3	3	.2805513	.0372785	.0728649	.1320956	.4290070
7	1	3	.4093184	.1992159	.0728649	.2608627	.5577741
7	2	3	.2418689	.0858775	.0728649	.0934132	.3903246
7	3	3	.1196217	.0359403	.0728649	-.0288340	.2680774
8	1	3	.8165057	.0625646	.0728649	.6680500	.9649614
8	2	3	.6292320	.0442129	.0728649	.4807763	.7776877
8	3	3	.5501967	.0675518	.0728649	.4017410	.6986524
9	1	3	.4175223	.1534466	.0728649	.2690666	.5659780
9	2	3	.2542256	.0865217	.0728649	.1057699	.4026813
9	3	3	.2085027	.0741280	.0728649	.0600470	.3569584
10	1	3	.5724427	.1907307	.0728649	.4239870	.7208984
10	2	3	.4607687	.1053929	.0728649	.3123130	.6092244
10	3	3	.4411107	.0346372	.0728649	.2926550	.5895664
11	1	3	.5037607	.0159870	.0728649	.3553050	.6522164
11	2	3	.5112377	.0375988	.0728649	.3627820	.6596934
11	3	3	.4495700	.0411898	.0728649	.3011143	.5980257
ventls by sqn							
CV	1	9	.3694098	.0917894	.0420686	.2836989	.4551208
CV	2	9	.2397596	.0676846	.0420686	.1540487	.3254706
CV	3	9	.2217838	.0530254	.0420686	.1360728	.3074947
CJV	1	9	.4762956	.0669168	.0420686	.3905846	.5620065
CJV	2	9	.3935968	.0637243	.0420686	.3078859	.4793078
CJV	3	9	.3190042	.0630403	.0420686	.2332933	.4047151
UHFJ	1	9	.6057113	.0926938	.0420686	.5200004	.6914223
UHFJ	2	9	.4516549	.0704776	.0420686	.3659439	.5373658
UHFJ	3	9	.4072858	.0837969	.0420686	.3215748	.4929967
Total		81	.3871669	.0140229	.0140229	.3585966	.4157372

Table 6a. Continued.

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3.1316148	12	.2609679	16.384	.0000
aals	2.1195172	8	.2649396	16.634	.0000
ventls	.6057387	2	.3028693	19.015	.0000
sqn	.4063589	2	.2031795	12.756	.0001
2-FACTOR INTERACTIONS	.9095322	36	.0252648	1.586	.0944
aals ventls	.7603480	16	.0475217	2.984	.0041
aals sqn	.1321107	16	.0082569	.518	.9177
ventls sqn	.0170736	4	.0042684	.268	.8964
RESIDUAL	.5096929	32	.0159279		
TOTAL (CORR.)	4.5508399	80			

0 missing values have been excluded.

Table 6b. Significance Test - F Test - a/A Ratio.

Table of means for a/A Ratio

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
amls						
1	9	.5457000	.1166664	.0480742	.4495153	.6418846
2	12	.2130527	.0339995	.0416335	.1297544	.2963510
3	6	.1915050	.0972340	.0588787	.0737034	.3093066
4	9	.1370275	.0238598	.0480742	.0408429	.2332121
6	9	.3722324	.0268131	.0480742	.2760478	.4684170
7	9	.2569364	.0761057	.0480742	.1607518	.3531211
8	9	.6653115	.0492770	.0480742	.5691269	.7614961
9	9	.2934169	.0636403	.0480742	.1972323	.3896015
10	9	.4914407	.0668975	.0480742	.3952560	.5876253
11	9	.4881894	.0193615	.0480742	.3920047	.5843740
ventls						
CV	30	.2559143	.0397739	.0263313	.2032318	.3085967
CJV	30	.3704274	.0371874	.0263313	.3177449	.4231099
UHFJV	30	.4722568	.0470061	.0263313	.4195744	.5249393
amls by ventls						
1 CV	3	.4529807	.2283630	.0832670	.2863841	.6195774
1 CJV	3	.2691594	.0112934	.0832670	.1025628	.4357561
1 UHFJ	3	.9149598	.0185237	.0832670	.7483631	1.0815564
2 CV	4	.0906745	.0199482	.0721114	-.0536024	.2349514
2 CJV	4	.2643058	.0636925	.0721114	.1200289	.4085828
2 UHFJ	4	.2841778	.0265883	.0721114	.1399008	.4284547
3 CV	2	.0654371	.0193508	.1019809	-.1386013	.2694755
3 CJV	2	.1196172	.0637227	.1019809	-.0844212	.3236556
3 UHFJ	2	.3894607	.2777305	.1019809	.1854223	.5934991
4 CV	3	.1279954	.0578178	.0832670	-.0386012	.2945921
4 CJV	3	.1112080	.0494673	.0832670	-.0553887	.2778046
4 UHFJ	3	.1718791	.0077544	.0832670	.0052825	.3384758
6 CV	3	.3293640	.0608801	.0832670	.1627674	.4959607
6 CJV	3	.3918519	.0312120	.0832670	.2252553	.5584486
6 UHFJ	3	.3954813	.0506475	.0832670	.2288846	.5620779
7 CV	3	.0754127	.0071906	.0832670	-.0911840	.2420093
7 CJV	3	.2710541	.0829344	.0832670	.1044575	.4376508
7 UHFJ	3	.4243425	.1788509	.0832670	.2577458	.5909391
8 CV	3	.5795198	.0844570	.0832670	.4129231	.7461164
8 CJV	3	.7262348	.0655544	.0832670	.5596382	.8928315
8 UHFJ	3	.6901800	.1089184	.0832670	.5235833	.8567766
9 CV	3	.0977670	.0214707	.0832670	-.0688296	.2643637
9 CJV	3	.4530240	.1090268	.0832670	.2864274	.6196207
9 UHFJ	3	.3294597	.0610498	.0832670	.1628630	.4960563
10 CV	3	.3013461	.0525908	.0832670	.1347494	.4679427
10 CJV	3	.5416763	.0159848	.0832670	.3750797	.7082730
10 UHFJ	3	.6312996	.1468741	.0832670	.4647029	.7978962
11 CV	3	.4302328	.0296448	.0832670	.2636362	.5968295
11 CJV	3	.5079129	.0315238	.0832670	.3413163	.6745096
11 UHFJ	3	.5264223	.0045828	.0832670	.3598257	.6930190
Total	90	.3661995	.0152024	.0152024	.3357833	.3966158

Table 7a. Analysis of Variance Table for a/A Ratio.
Three Factor Balanced Design.

Analysis of Variance for aarnew

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS	3.1658474	11	.2878043	13.837	.0000
amls	2.4629813	9	.2736646	13.157	.0000
ventls	.7028661	2	.3514330	16.896	.0000
2-FACTOR INTERACTIONS	.7907706	18	.0439317	2.112	.0162
amls ventls	.7907706	18	.0439317	2.112	.0162
RESIDUAL	1.2480114	60	.0208002		
TOTAL (CORR.)	5.2046294	89			

0 missing values have been excluded.

Table 7b. Significance Test - F Test a/A Ratio.

Two-Sample Analysis Results

		CV	UHFJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	0.255914	0.472257	0.364086
	Variance	0.0474589	0.0662873	0.0568731
	Std. Deviation	0.217851	0.257463	0.238481
	Median	0.178977	0.42485	0.310624

		99 Percent	
Conf. Interval For Diff. in Means:			
(Equal Vars.)	Sample 1 - Sample 2	-0.380363 -0.052322	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	-0.380516 -0.0521696	56.5 D.F.

		95 Percent		
Conf. Interval for Ratio of Variances:				
	Sample 1 ÷ Sample 2	0.340768 1.50424	29	29 D.F.

Hypothesis Test for HO: Diff = 0 vs Alt: NE at Alpha = 0.01
Computed t statistic = -3.51345
Sig. Level = 8.64609E-4
so reject HO.

		CJV	UHFJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	0.370427	0.472257	0.421342
	Variance	0.041487	0.0662873	0.0538872
	Std. Deviation	0.203684	0.257463	0.232136
	Median	0.353796	0.42485	0.386262

		90 Percent	
Conf. Interval For Diff. in Means:			
(Equal Vars.)	Sample 1 - Sample 2	-0.20204 -1.6188E-3	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	-0.202126 -1.53256E-3	55.1 D.F.

		95 Percent		
Conf. Interval for Ratio of Variances:				
	Sample 1 ÷ Sample 2	0.297888 1.31495	29	29 D.F.

Hypothesis Test for HO: Diff = 0 vs Alt: NE at Alpha = 0.1
Computed t statistic = -1.69893
Sig. Level = 0.0946903
so reject HO.

		CV	CJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	0.255914	0.370427	0.313171
	Variance	0.0474589	0.041487	0.044473
	Std. Deviation	0.217851	0.203684	0.210886
	Median	0.178977	0.353796	0.279111

		95 Percent	
Conf. Interval For Diff. in Means:			
(Equal Vars.)	Sample 1 - Sample 2	-0.223533 -5.49374E-3	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	-0.223543 -5.48327E-3	57.7 D.F.

		95 Percent		
Conf. Interval for Ratio of Variances:				
	Sample 1 ÷ Sample 2	0.544473 2.40344	29	29 D.F.

Hypothesis Test for HO: Diff = 0 vs Alt: NE at Alpha = 0.05
Computed t statistic = -2.10307
Sig. Level = 0.0398091
so reject HO.

Table 7c. Significance Test - T Test - a/A Ratio.

Table of means for BPF

Level	Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
amis						
1	9	3029.333	840.1590	307.74585	2401.535	3657.132
2	9	2353.556	611.7464	307.74585	1725.757	2981.354
4	9	2306.000	423.9774	307.74585	1678.201	2933.799
6	9	1468.444	293.9405	307.74585	840.646	2096.243
7	9	5995.111	840.6977	307.74585	5367.312	6622.910
8	9	2783.778	846.1962	307.74585	2155.979	3411.576
9	9	7044.556	1483.1340	307.74585	6416.757	7672.354
10	9	2549.778	574.8494	307.74585	1921.979	3177.576
11	9	3416.222	279.6631	307.74585	2788.424	4044.021
ventls						
CV	27	5828.852	604.3654	177.67715	5466.392	6191.312
CJV	27	2774.037	361.7821	177.67715	2411.577	3136.497
UHFJV	27	1712.704	231.6688	177.67715	1350.244	2075.163
sqn						
1	27	3356.481	542.3135	177.67715	2994.022	3718.941
2	27	3373.185	544.8269	177.67715	3010.725	3735.645
3	27	3585.926	555.7968	177.67715	3223.466	3948.386
amis by ventls						
1 CV	3	5693.000	1324.7313	533.03145	4605.621	6780.379
1 CJV	3	2831.667	299.6922	533.03145	1744.288	3919.046
1 UHFJ	3	563.333	134.1794	533.03145	-524.046	1650.712
2 CV	3	4722.000	367.4783	533.03145	3634.621	5809.379
2 CJV	3	1504.000	175.3207	533.03145	416.621	2591.379
2 UHFJ	3	834.667	76.6645	533.03145	-252.712	1922.046
4 CV	3	3922.000	294.9328	533.03145	2834.621	5009.379
4 CJV	3	1604.000	128.8462	533.03145	516.621	2691.379
4 UHFJ	3	1392.000	289.2525	533.03145	304.621	2479.379
6 CV	3	2490.667	297.3518	533.03145	1403.288	3578.046
6 CJV	3	1198.667	118.2446	533.03145	111.288	2286.046
6 UHFJ	3	716.000	304.0839	533.03145	-371.379	1803.379
7 CV	3	7814.333	1528.1935	533.03145	6726.954	8901.712
7 CJV	3	6939.667	467.2659	533.03145	5852.288	8027.046
7 UHFJ	3	3231.333	86.2947	533.03145	2143.954	4318.712
8 CV	3	5785.667	1218.6312	533.03145	4698.288	6873.046
8 CJV	3	1564.000	421.5286	533.03145	476.621	2651.379
8 UHFJ	3	1001.667	303.7600	533.03145	-85.712	2089.046
9 CV	3	12903.333	155.2443	533.03145	11815.954	13990.712
9 CJV	3	4536.333	297.1365	533.03145	3448.954	5623.712
9 UHFJ	3	3694.000	602.0872	533.03145	2606.621	4781.379
10 CV	3	4790.333	271.6305	533.03145	3702.954	5877.712
10 CJV	3	1534.333	305.3754	533.03145	446.954	2621.712
10 UHFJ	3	1324.667	149.4259	533.03145	237.288	2412.046
11 CV	3	4338.333	306.0405	533.03145	3250.954	5425.712
11 CJV	3	3253.667	82.5355	533.03145	2166.288	4341.046
11 UHFJ	3	2656.667	333.5353	533.03145	1569.288	3744.046
Total	81	3438.531	102.5820	102.58195	3229.265	3647.797

Table 8a. Analysis of Variance Table - Flow Through Bronchopleural Fistula - Three Factor Balanced Design.

Table of means for BPF

Level		Count	Average	Stnd. Error (internal)	Stnd. Error (pooled s)	95 Percent Confidence for mean	
amis by sqn							
1	1	3	2281.000	994.9675	533.03145	1193.621	3368.379
1	2	3	3258.000	1649.8948	533.03145	2170.621	4345.379
1	3	3	3549.000	2077.7683	533.03145	2461.621	4636.379
2	1	3	2257.667	1213.5161	533.03145	1170.288	3345.046
2	2	3	2625.667	1391.6449	533.03145	1538.288	3713.046
2	3	3	2177.333	1012.1068	533.03145	1089.954	3264.712
4	1	3	2037.000	728.0730	533.03145	949.621	3124.379
4	2	3	2319.333	828.3883	533.03145	1231.954	3406.712
4	3	3	2561.667	933.7088	533.03145	1474.288	3649.046
6	1	3	1919.667	577.2008	533.03145	832.288	3007.046
6	2	3	1215.333	455.4047	533.03145	127.954	2302.712
6	3	3	1270.333	585.4919	533.03145	182.954	2357.712
7	1	3	6896.667	2081.7988	533.03145	5809.288	7984.046
7	2	3	4920.667	855.3098	533.03145	3833.288	6008.046
7	3	3	6168.000	1554.7566	533.03145	5080.621	7255.379
8	1	3	2382.667	908.1897	533.03145	1295.288	3470.046
8	2	3	3238.667	2429.6649	533.03145	2151.288	4326.046
8	3	3	2730.000	1295.8175	533.03145	1642.621	3817.379
9	1	3	6410.667	3119.5772	533.03145	5323.288	7498.046
9	2	3	7113.333	2947.5448	533.03145	6025.954	8200.712
9	3	3	7609.667	2759.2587	533.03145	6522.288	8697.046
10	1	3	2454.667	1039.9174	533.03145	1367.288	3542.046
10	2	3	2621.667	1369.6399	533.03145	1534.288	3709.046
10	3	3	2573.000	1000.3519	533.03145	1485.621	3660.379
11	1	3	3568.333	440.4242	533.03145	2480.954	4655.712
11	2	3	3046.000	522.0013	533.03145	1958.621	4133.379
11	3	3	3634.333	806.7878	533.03145	2546.954	4721.712
ventls by sqn							
CV	1	9	5591.889	1160.4807	307.74585	4964.090	6219.688
CV	2	9	5914.000	1046.6809	307.74585	5286.201	6541.799
CV	3	9	5980.667	1052.7103	307.74585	5352.868	6608.465
CJV	1	9	2868.111	535.3736	307.74585	2240.312	3496.910
CJV	2	9	2563.556	621.9363	307.74585	1935.757	3191.354
CJV	3	9	2890.444	733.7139	307.74585	2262.646	3518.243
UHFJ	1	9	1609.444	377.0608	307.74585	981.646	2237.243
UHFJ	2	9	1642.000	385.0691	307.74585	1014.201	2269.799
UHFJ	3	9	1886.667	476.5430	307.74585	1258.868	2514.465
Total		81	3438.531	102.5820	102.58195	3229.265	3647.797

Table 8a. Continued.

Analysis of Variance for BPF

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
COVARIATES	1.1390E0008	1	1.1390E0008	133.625	.0000
aarnew	1.1390E0008	1	1.1390E0008	133.625	.0000
MAIN EFFECTS	4.0049E0008	12	33373930	39.154	.0000
amls	2.3673E0008	8	29591422	34.717	.0000
ventls	1.1676E0008	2	58378604	68.490	.0000
sqn	2.8188E0006	2	1409393	1.654	.2078
2-FACTOR INTERACTIONS	91770446	36	2549179.1	2.991	.0013
amls ventls	77814387	16	4863399.2	5.706	.0000
amls sqn	12898563	16	806160.2	.946	.5317
ventls sqn	650476	4	162619.0	.191	.9414
RESIDUAL	26423395	31	852367.59		

0 missing values have been excluded.

COVARIATES	coefficient
a/A Ratio	-2817.9675

Table 8b. Significance Test - F Test - Flow Through Bronchopleural Fistula.

Two-Sample Analysis Results

		CV	UHFJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	5501.7	1675.4	3588.55
	Variance	9.84676E6	1.36272E6	5.60474E6
	Std. Deviation	3137.95	1167.36	2367.43
	Median	4519	1346	3066.5

Conf. Interval For Diff. in Means:	99 Percent		
(Equal Vars.)	Sample 1 - Sample 2	2198.04 5454.56	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	2165.87 5486.73	36.9 D.F.

Conf. Interval for Ratio of Variances:	95 Percent		
	Sample 1 ÷ Sample 2	3.43919 15.1815	29 29 D.F.

Hypothesis Test for HO: Diff = 0	Computed t statistic = 6.25961
vs Alt: NE	Sig. Level = 5.06755E-8
at Alpha = 0.01	so reject HO.

		CJV	UHFJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	2737.5	1675.4	2206.45
	Variance	3.21029E6	1.36272E6	2.28651E6
	Std. Deviation	1791.73	1167.36	1512.12
	Median	2059.5	1346	1758

Conf. Interval For Diff. in Means:	99 Percent		
(Equal Vars.)	Sample 1 - Sample 2	22.1048 2102.1	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	16.3237 2107.88	49.9 D.F.

Conf. Interval for Ratio of Variances:	95 Percent		
	Sample 1 ÷ Sample 2	1.12126 4.94955	29 29 D.F.

Hypothesis Test for HO: Diff = 0	Computed t statistic = 2.72035
vs Alt: NE	Sig. Level = 8.59223E-3
at Alpha = 0.01	so reject HO.

		CV	CJV	Pooled
Sample Statistics:	Number of Obs.	30	30	60
	Average	5501.7	2737.5	4119.6
	Variance	9.84676E6	3.21029E6	6.52852E6
	Std. Deviation	3137.95	1791.73	2555.1
	Median	4519	2059.5	3367

Conf. Interval For Diff. in Means:	99 Percent		
(Equal Vars.)	Sample 1 - Sample 2	1006.87 4521.53	58 D.F.
(Unequal Vars.)	Sample 1 - Sample 2	991.367 4537.03	46.1 D.F.

Conf. Interval for Ratio of Variances:	95 Percent		
	Sample 1 ÷ Sample 2	1.45989 6.44432	29 29 D.F.

Hypothesis Test for HO: Diff = 0	Computed t statistic = 4.18994
vs Alt: NE	Sig. Level = 9.6297E-5
at Alpha = 0.01	so reject HO.

Table 8c. Significance Tests - T Test - Flow Through Bronchopleural Fistula.

SIGNIFICANCE LEVELS FOR VENTILATOR DIFFERENCES

(TWO SIDED TEST)

a / A RATIO

UHFJV vs. CV: $\alpha = 0.01$

CJV vs. CV: $\alpha = 0.05$

UHFJV vs. CJV: $\alpha = 0.10$

FLOW THROUGH BRONCHOPLEURAL FISTULA

UHFJV vs. CV: $\alpha = 0.01$

CJV vs. CV: $\alpha = 0.01$

UHFJV vs. CJV: $\alpha = 0.01$

Table 9.

APPENDIX I

Following the development of our high frequency jet ventilator, laboratory tests were conducted to determine the ventilator's capabilities. The ventilator was tested on rigid systems and systems whose compliance was similar to that of the lung. Ventilation was also done in a system consisting of high resistance/low compliance chamber in parallel with high compliance/low resistance chamber. This scenario is represenative of the most difficult patients to ventilate in an ICU setting. The studies demonstrated that the ventilator was capable of delivering tidal volumes and flows equal to or surpassing existing jet ventilators. The ventilator adds on extended frequency both on the high and low side increasing its flexibility over standard jet ventilators. Two hundred fifty (250) to five hundred (500) ml of CO_2 per minute were pumped into the jars or the elastic lung models. At all frequencies our ventilator was able to achieve adequate ventilation as demonstrated by equilibrium $PCO_2 < 5\%$.

Following this, the first of three groups of animal testing was begun. The pig was chosen as our test animal because its lungs are less compliant than those of a human and there is less collateal ventilation between alveoli, creating a situation similar to a diseased human lung. Five 40-pound pigs were anesthestisized using nembutal. Arterial and venous lines were placed. The pigs were monitored electrocardiographically. Ventilation was accomplished with FIO_2 of .21. The frequency of the jet ventilator was set at either 10 or 20 Hz. Inspiratory time ratio was 30% and the driving pressure (20-50 PSI) was set to achieve adequate ventilation.

Four pigs were ventilated for 48 hours, one for 30 hours. Animals were monitored at frequent intervals with respect to arterial blood gases, blood pressure, and hemodynamic side effects. At the end of the test period, the animals were sacrificed and autopsies of the lung were performed to determine the presence of untoward effects from the jet ventilation. The studies demonstrated no evidence of barotrauma was present at the end of 48 hours of ventilation. Arterial blood pressures and hemodynamic status were stable throughout. Arterial blood gases demonstrated that the alveolar-arterial gradient was significantly smaller on our ventilator than on conventional ventilation. These data suggested that our ventilation may have eliminated a significant degree of ventilation perfusion mismatching. In one pig a mild

tracheitis developed at the end of the endotracheal tube. This was at least in part due to lack of humidification of the gases used during this particular experiment. These animals were compared to a previous study performed at Hartford Hospital with conventional ventilators. The pigs ventilated conventionally demonstrated significant evidence of barotrauma. Our conclusion from the study is that our ventilator can ventilate animals for a prolonged period of time and maintain adequate arterial oxygen tensions and that atelectasis and other forms of trauma to the lung are not common with this mode of ventilation. In fact, when compared to previous studies done on conventional ventilators, there appeared to be less trauma to the animal during this form of ventilation.

The next experiment was performed on five 40-pound pigs. The pigs were anesthesized with nembutol. Arterial and venous lines were introduced. A piano wire was inserted bronchoscopically into either the right or left main stem bronchus and was allowed to pass through the lung parenchyma and out through the chest wall. Over this piano wire a catheter with a known diameter tip was then passed through the chest wall and was bronchoscopically observed to occlude an airway of similar size to the measured diameter of the tip of the catheter. These catheters, usually 3 or 4, were then connected to pressure transducers and airway pressure measurements were made during various maneuvers on the high frequency jet ventilator. The animals were ventilated for varying times from 1 Hz to 30 Hz, and pressure measurements were taken from the endotracheal tube as well as from the peripheral catheters which were inserted according to the protocol. ABGs were monitored on all frequencies. All animals developed broncho-pleural fistulae due to the passing of the piano wire through the chest wall. Chest tubes were inserted to compensate. In spite of the fact that these animals had bilateral broncho-pleural fistulae, adequate ventilation was maintained in all experimental animals at all frequencies. Airway pressure measuremnts were obtained and allowed us to observe the effects of increasing frequency and change in inspiratory time with respect to airway pressure and arterial blood gas analysis.

Another sequence of experiments included a protocol in which 80-pound pigs were given intravenous oleic acid to induce an ARDS-like syndrome. A comparison was made between conventional ventilation and our ventilator with respect to hemodynamic variables, oxygenation, and degree of decompensation for a given lung injury. Twenty animals were studied. The data showed that the

mean cardiac output was higher using ultra-high frequency jet ventilation as compared to conventional ventilation with a significance level of $\alpha=.01$. The a/A ratio was better in the ultra-high frequency ventilation group and QS/QT (the left to right shunt) was lower, but in the small group of animals we were unable to reach statistical significance in the variables.

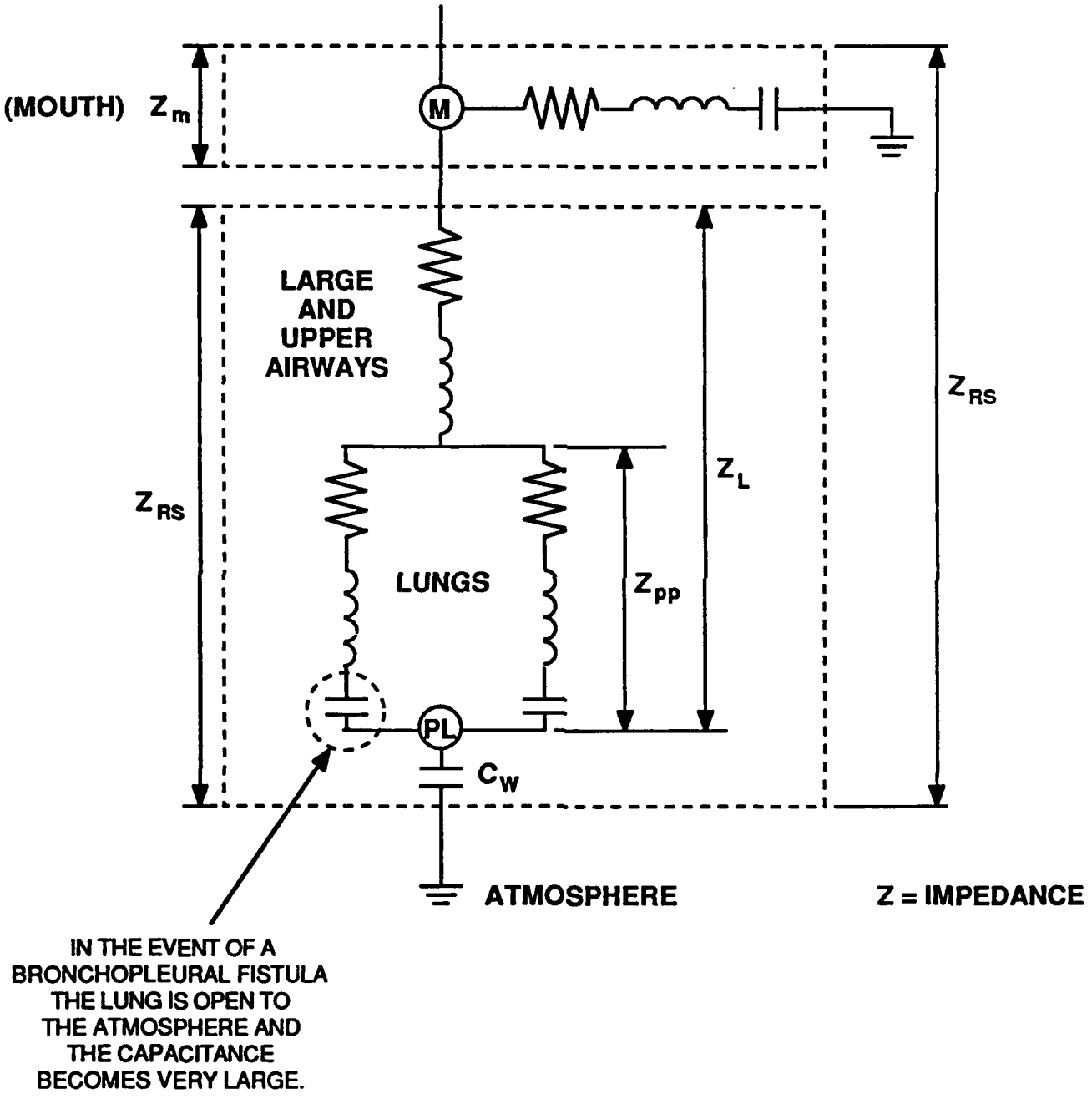

Fig. 1. Electrical Analog of Lung System.

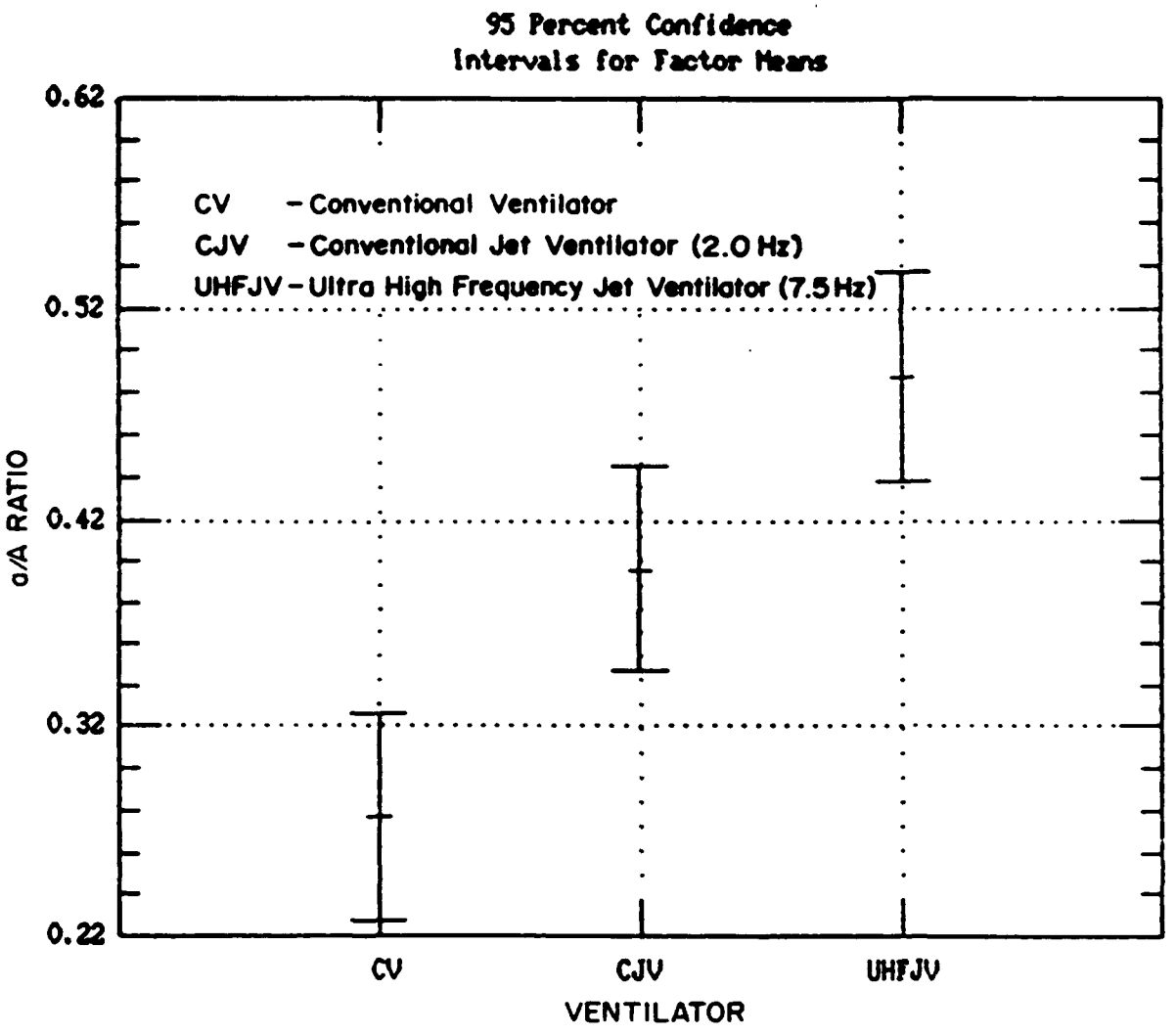

Fig. 2. a/A Ratio for Different Ventilators.

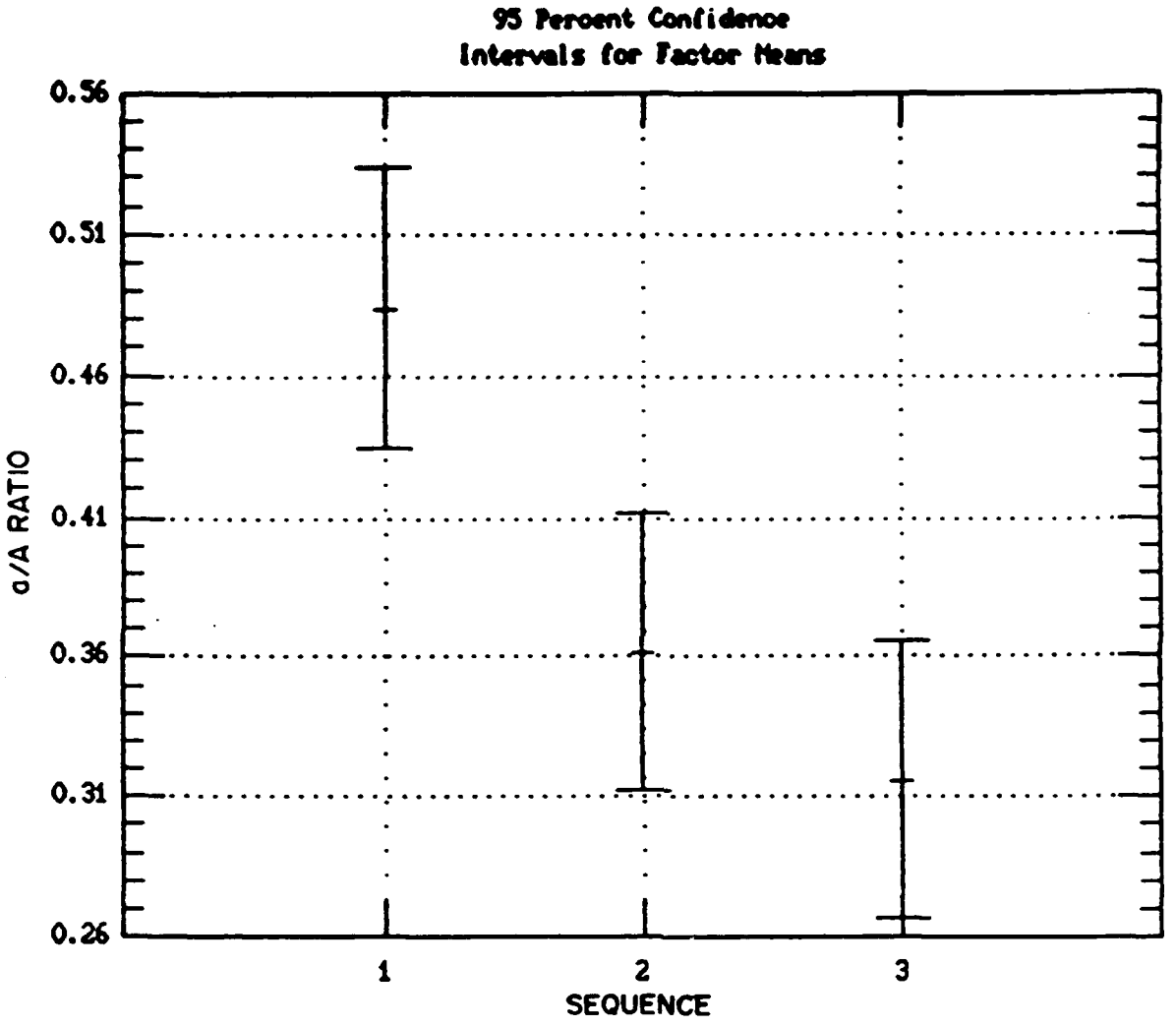

Fig. 3. a/A Ratio for Different Sequences.

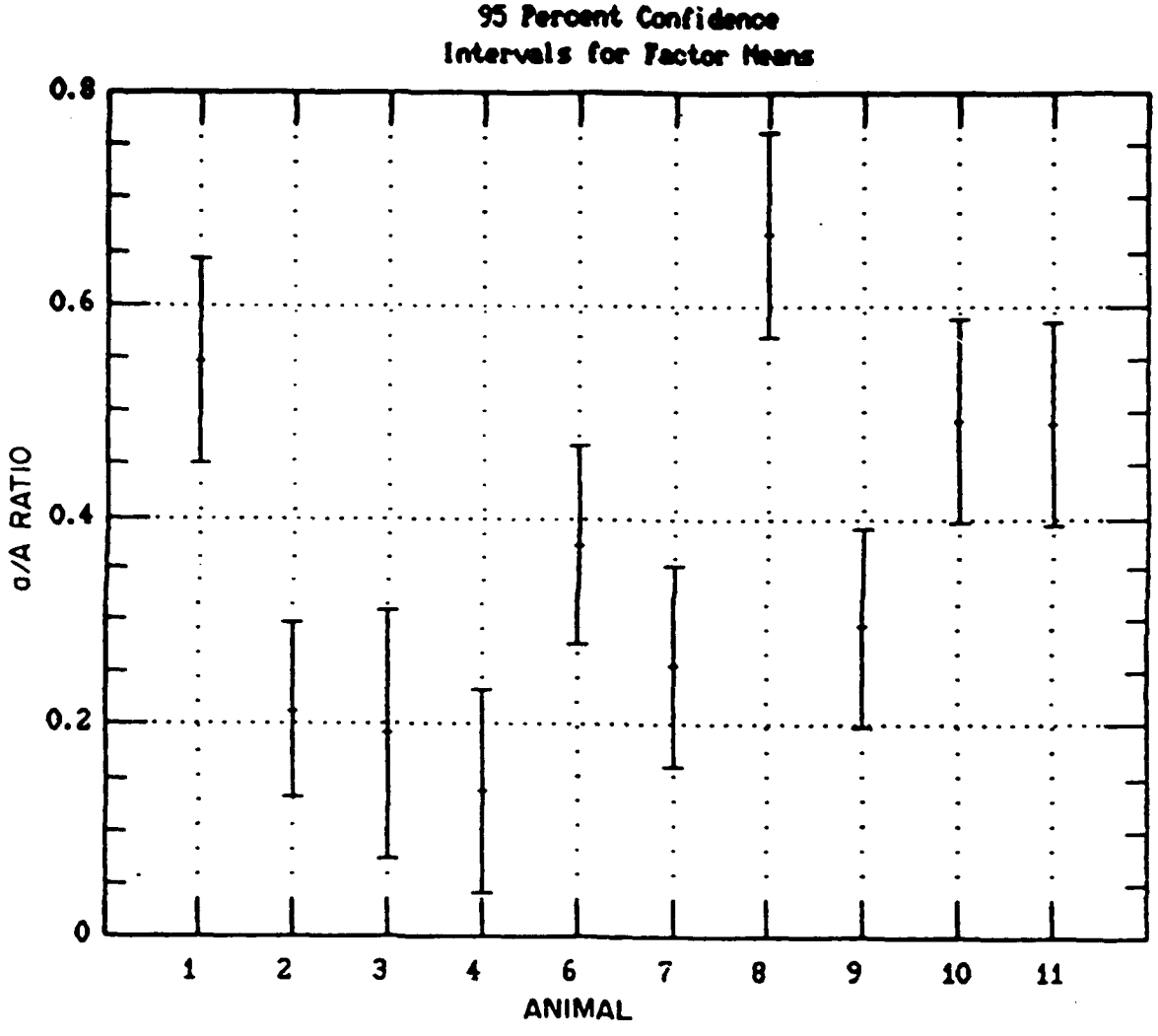

Fig. 4. a/A Ratio for Different Animals.

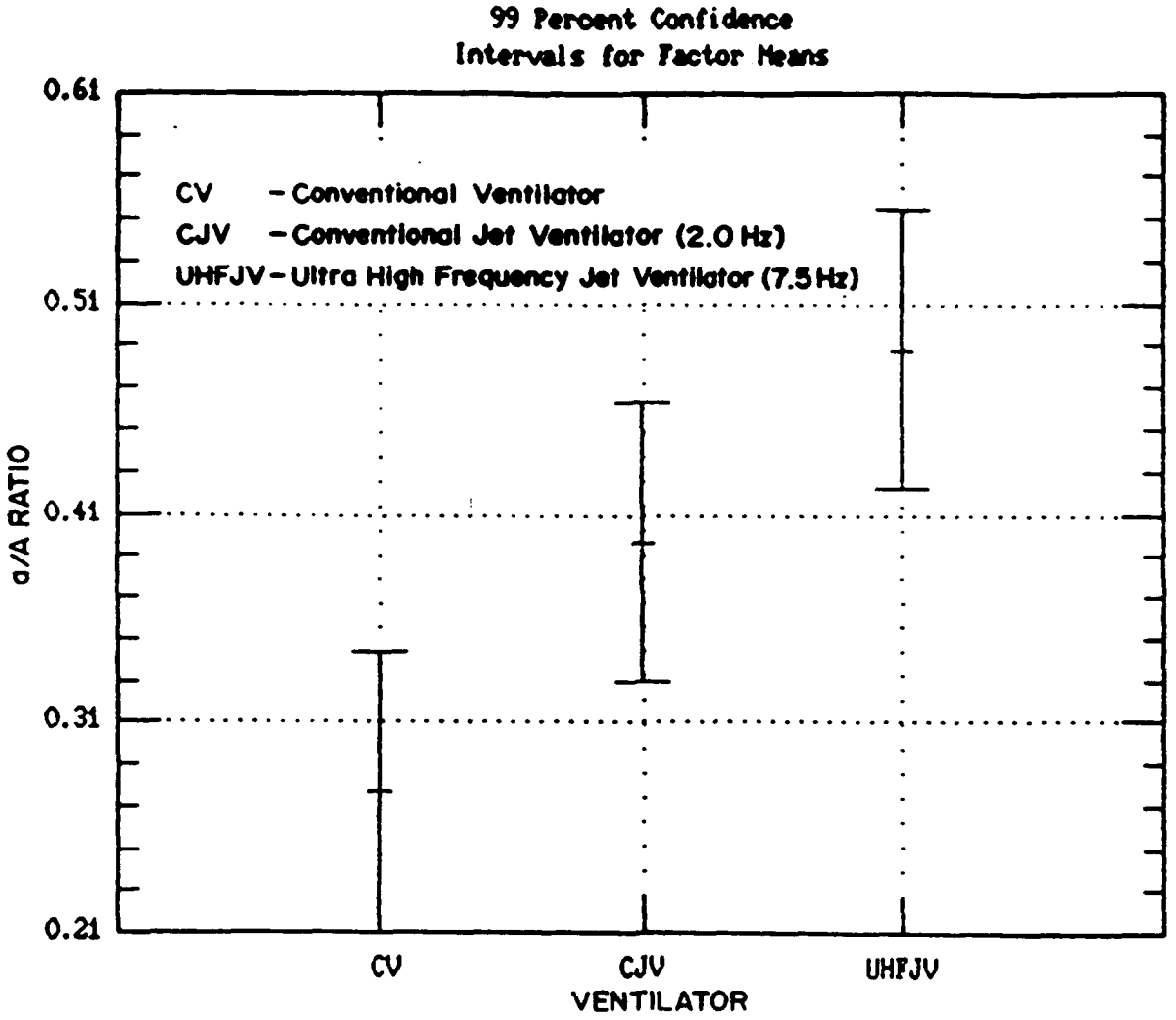

Fig. 5. a/A Ratio for Different Ventilators.

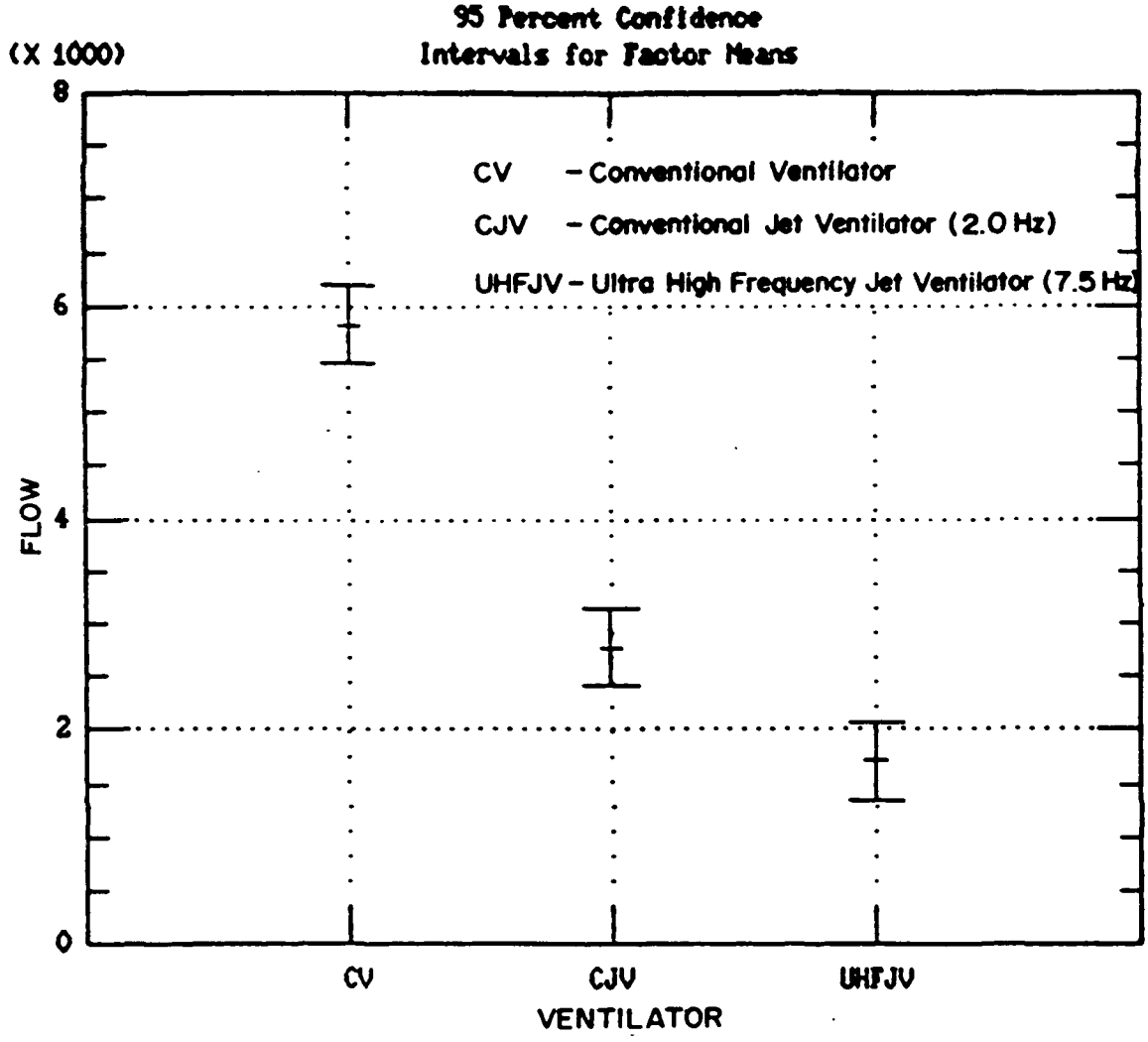

Fig. 6. Flow Through Fistula for Different Ventilators.

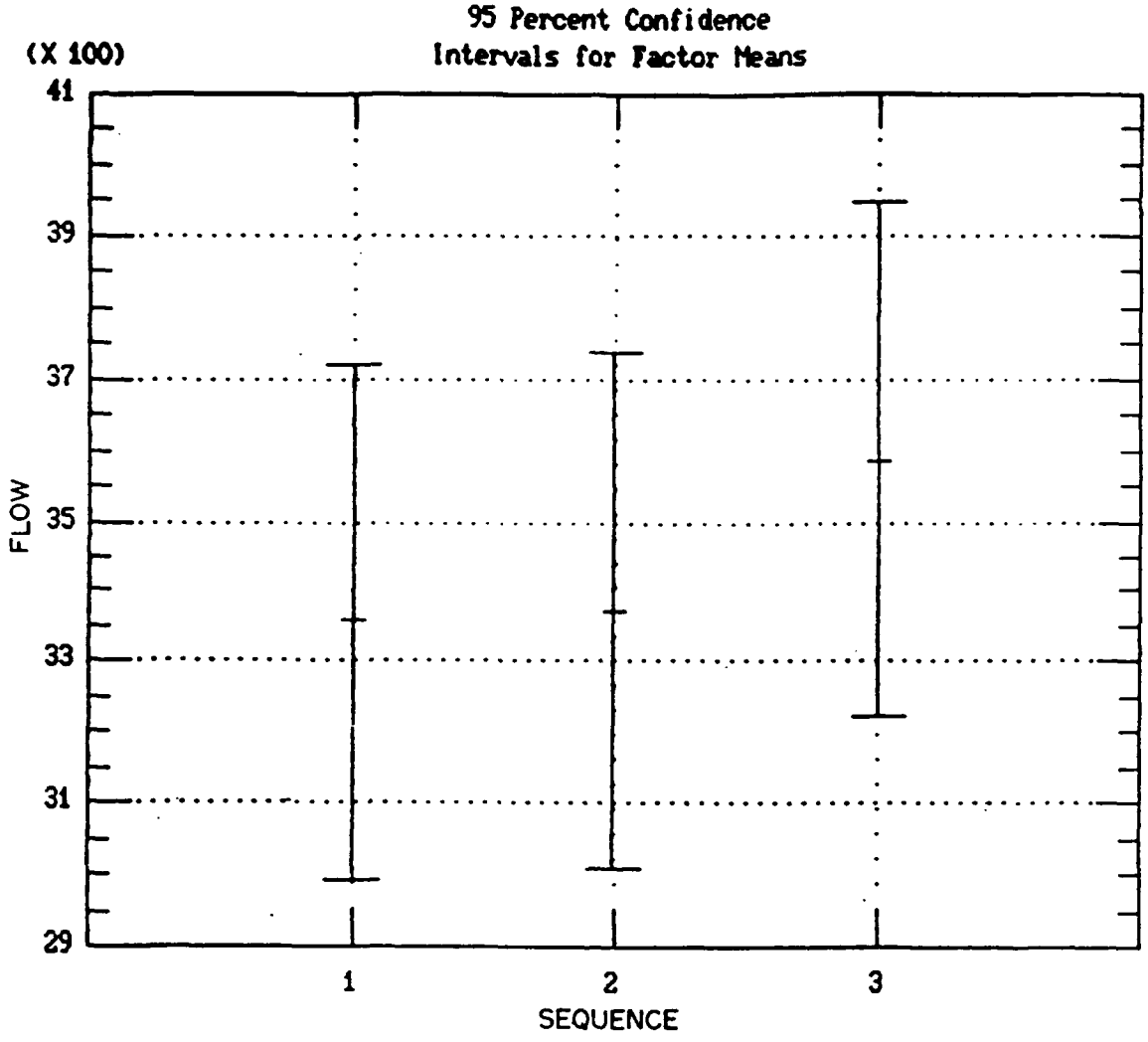

Fig. 7. Flow Through Fistula for Different Sequences.

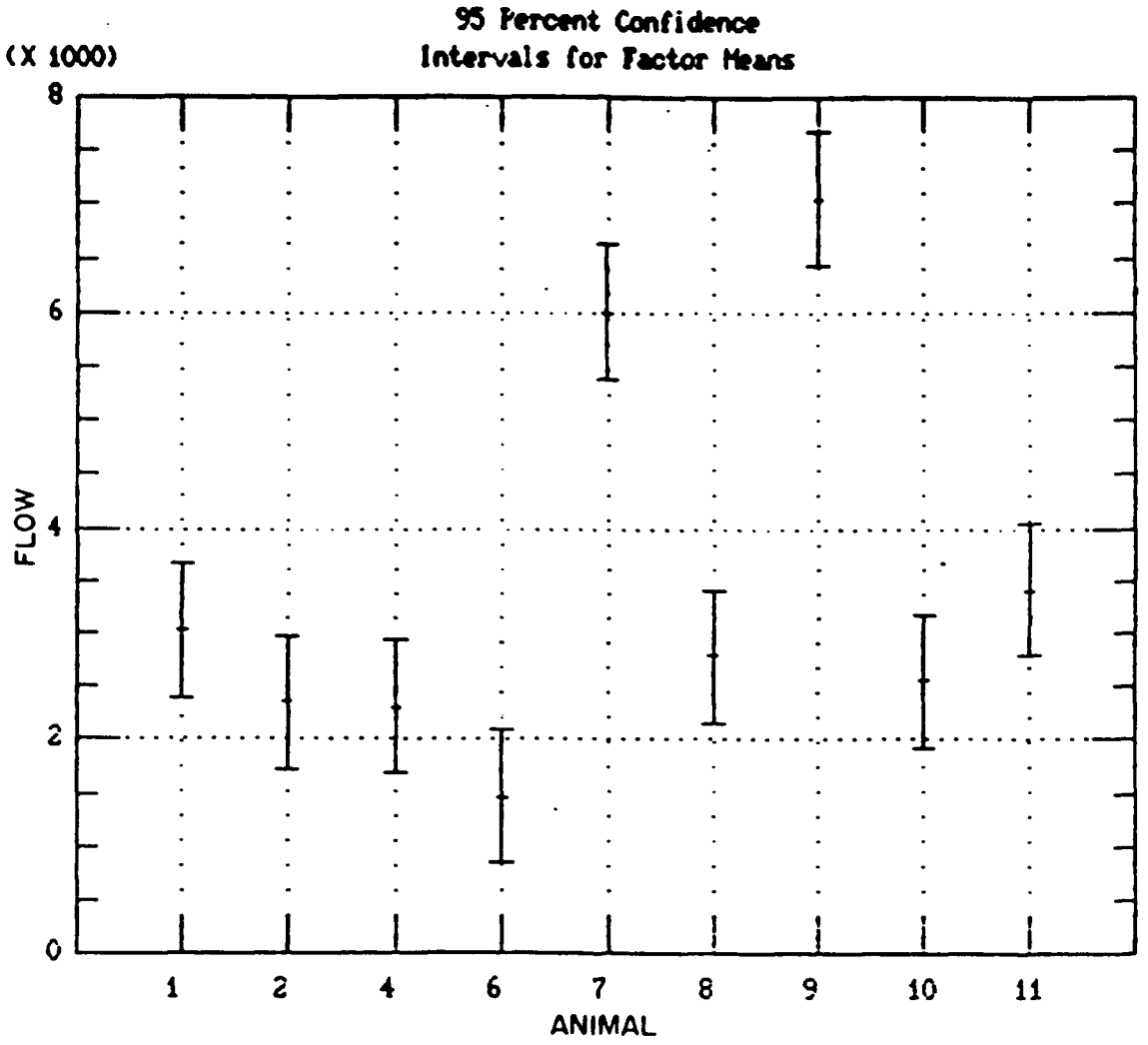

Fig. 8. Flow Through Fistula for Different Animals.

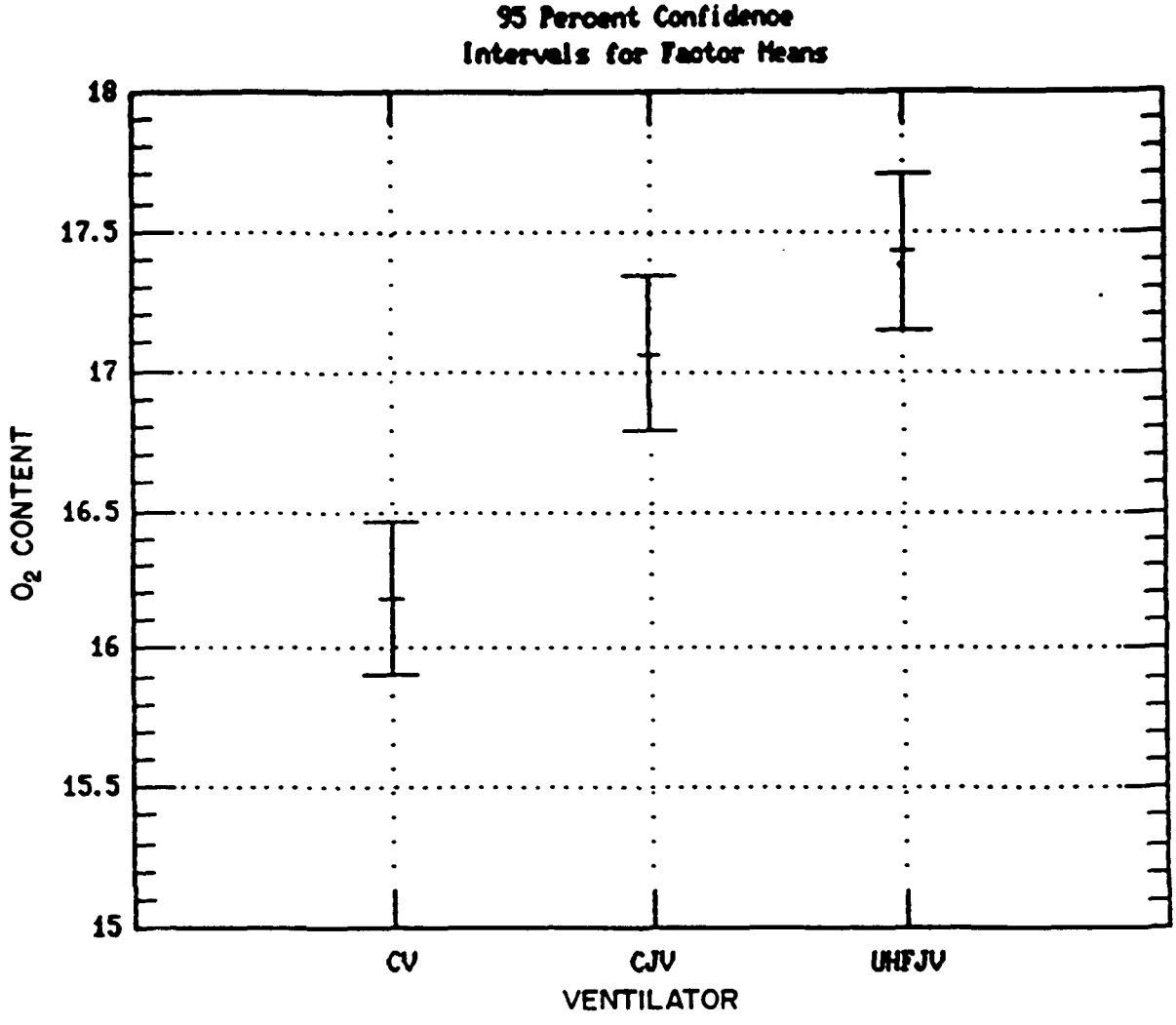

Fig. 9. O_2 Delivery for Different Ventilators.

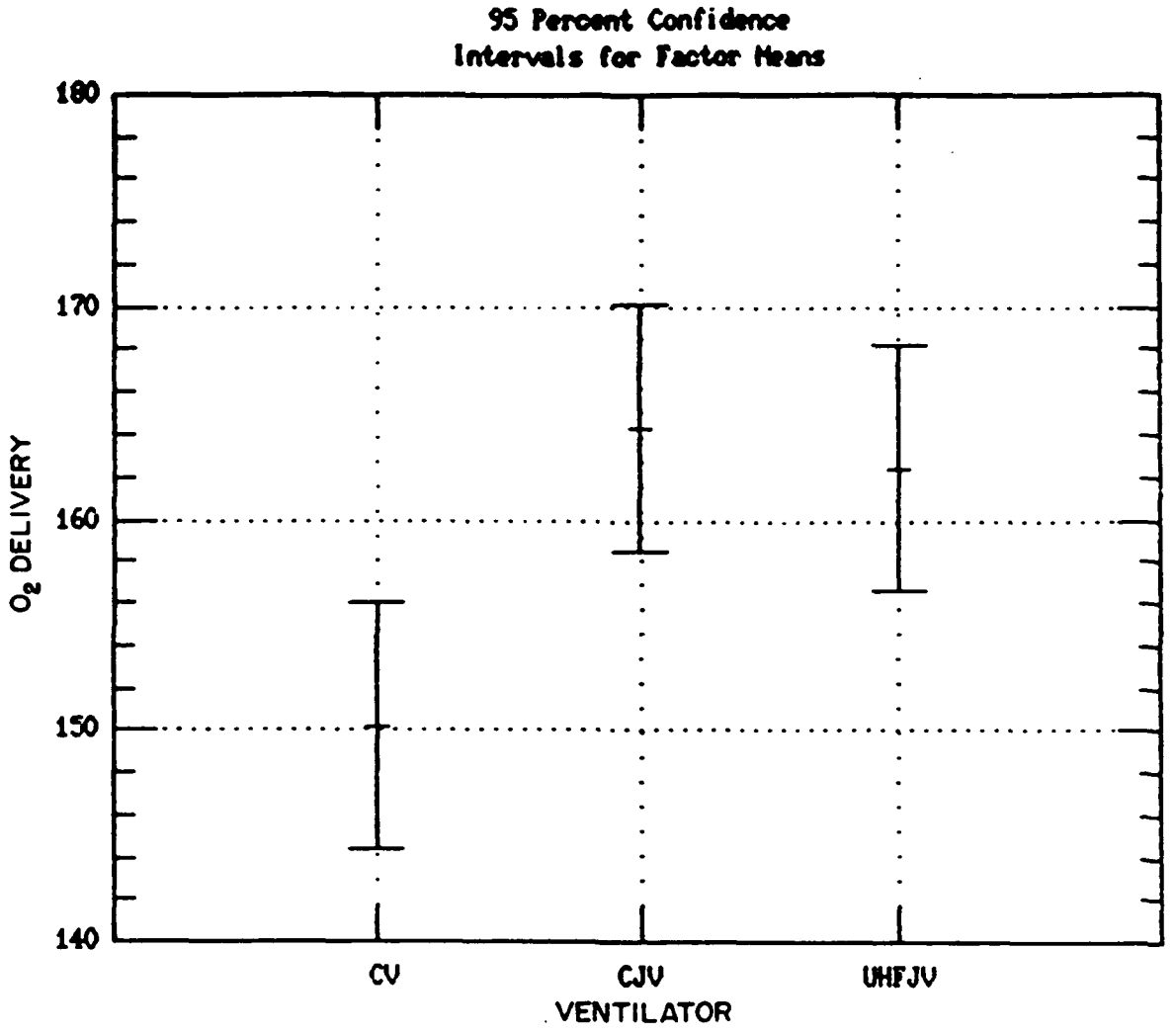

Fig. 10. O_2 Content for Different Ventilators.

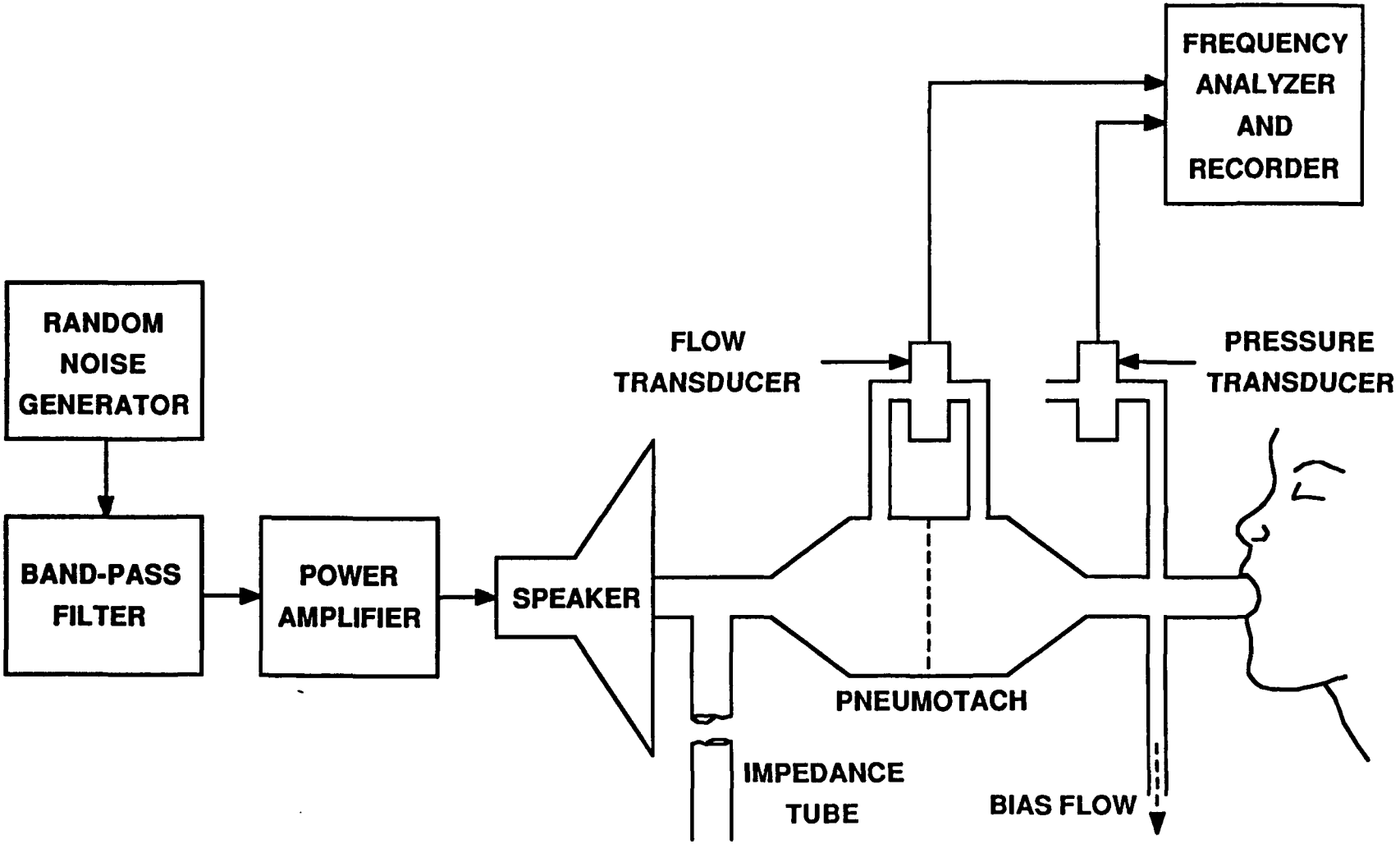

Fig. 11. Schematic of Resonant Frequency Measuring Apparatus.

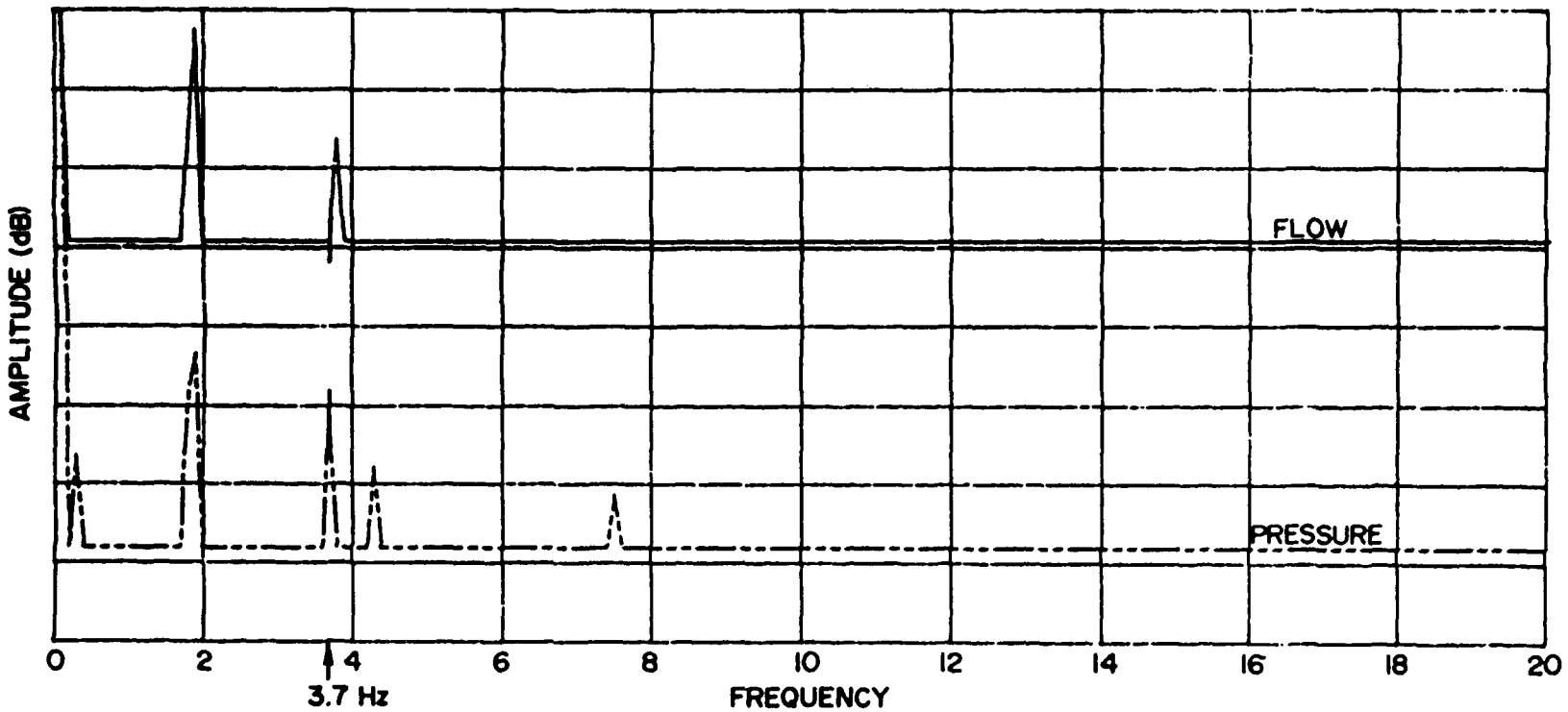

Fig. 12. Amplitude vs. Frequency (Unconstrained Chest Wall).

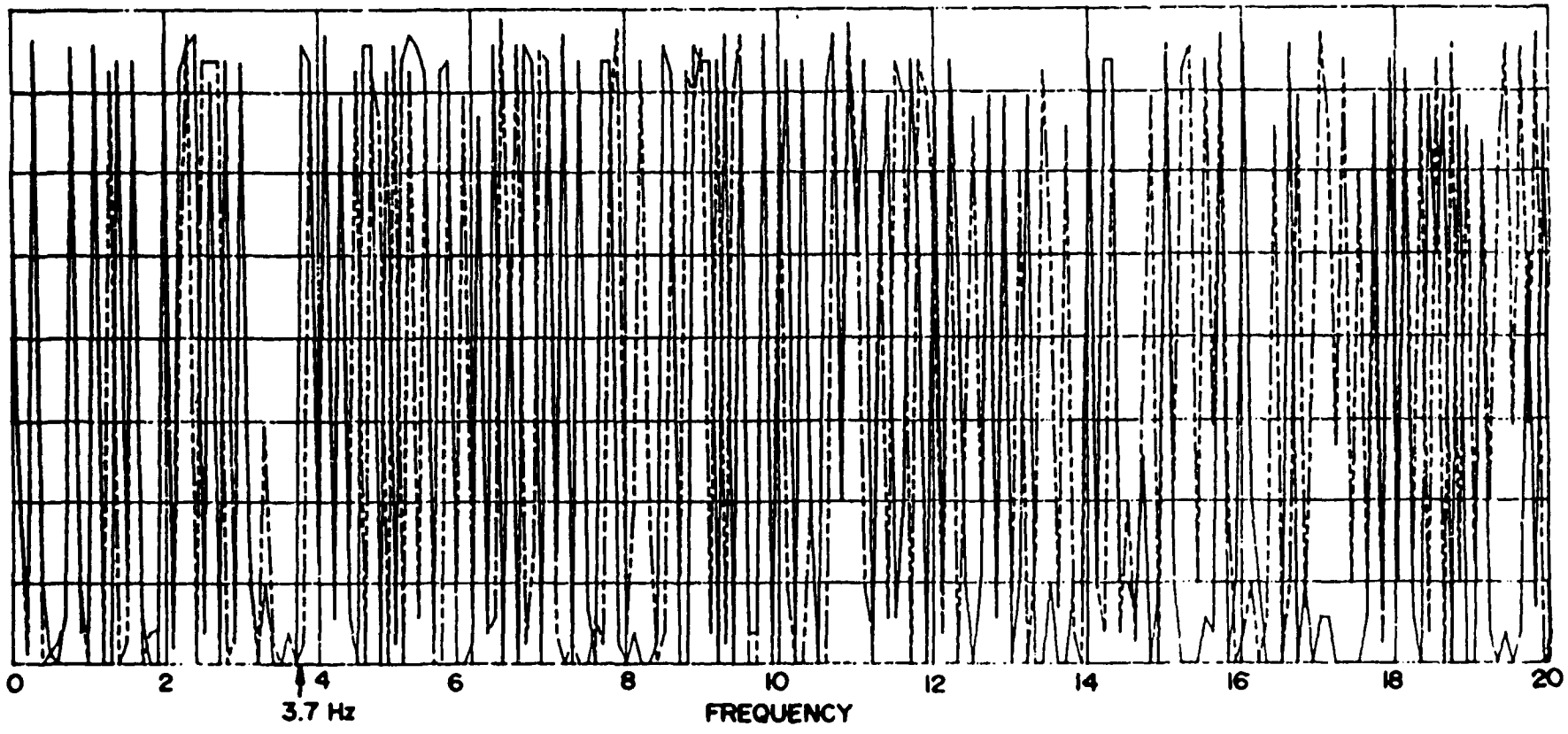

Fig. 13. Phase Angle vs. Frequency (Unconstrained Chest Wall)

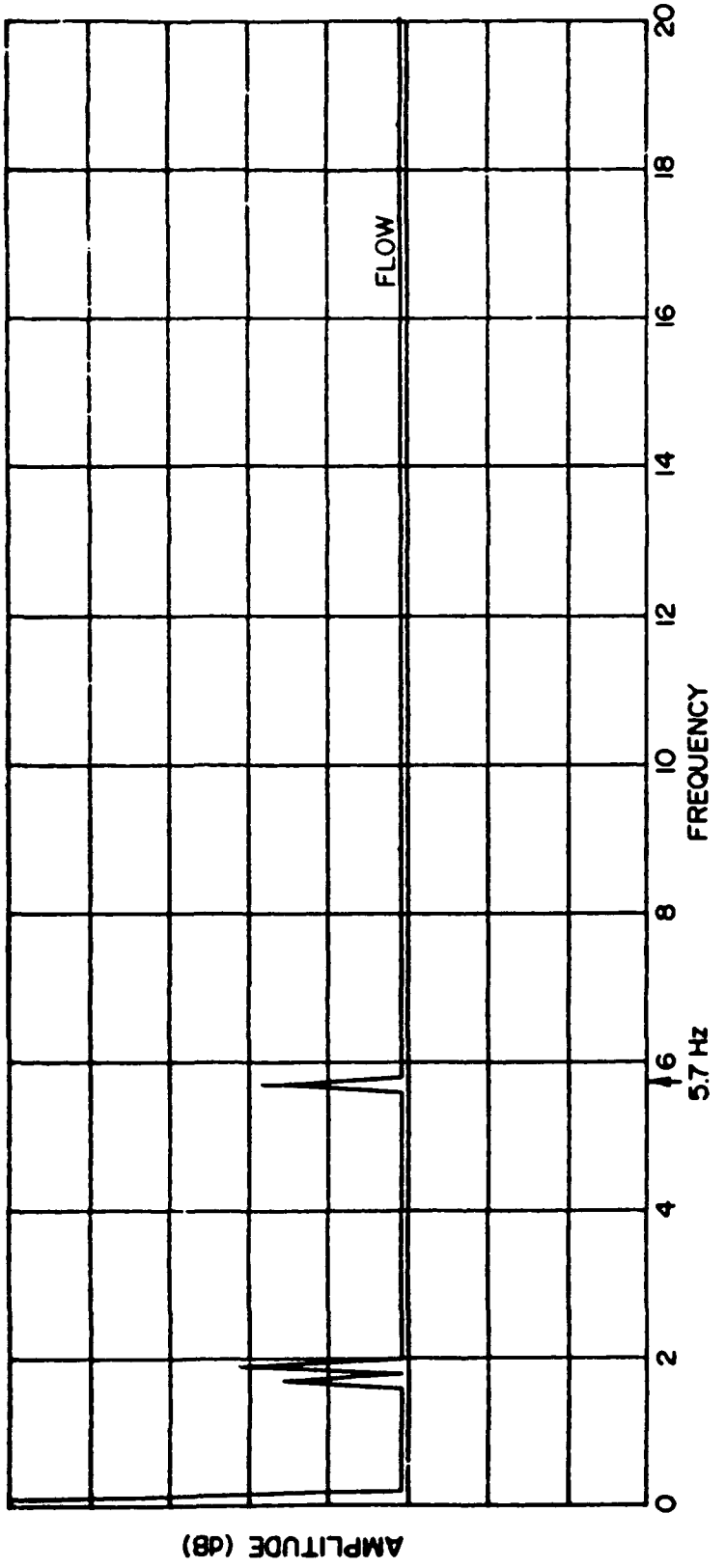

Fig. 14. Amplitude vs. Frequency (Constrained Chest Wall).